

# Keck Spectroscopy of Faint $3 < z < 7$ Lyman Break Galaxies: - I. New constraints on cosmic reionisation from the luminosity and redshift-dependent fraction of Lyman- $\alpha$ emission

Daniel P. Stark<sup>1\*</sup>, Richard S. Ellis<sup>2</sup>, Kuenley Chiu<sup>2</sup>, Masami Ouchi<sup>3,4</sup>, Andrew Bunker<sup>5</sup>

<sup>1</sup> *Kavli Institute of Cosmology & Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*

<sup>2</sup> *California Institute of Technology, 1200 E. California Blvd. Pasadena, CA 91125, USA*

<sup>3</sup> *Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street Pasadena, CA 91101 USA*

<sup>4</sup> *Carnegie Fellow*

<sup>5</sup> *Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

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## ABSTRACT

We present the first results of a new Keck spectroscopic survey of UV faint Lyman break galaxies in the redshift range  $3 < z < 7$ . Combined with earlier Keck and published ESO VLT data, our spectroscopic sample contains more than 600 dropouts offering new insight into the nature of sub- $L^*$  sources typical of those likely to dominate the cosmic reionisation process. In this first paper in a series discussing these observations, we characterise the fraction of strong Ly $\alpha$  emitters within the continuum-selected dropout population. By quantifying how the “Ly $\alpha$  fraction” varies with redshift, we seek to constrain changes in Ly $\alpha$  transmission associated with reionisation. In order to distinguish the effects of reionisation from other factors which affect the Ly $\alpha$  fraction (e.g. dust, ISM kinematics), we study the luminosity and redshift-dependence of the Ly $\alpha$  fraction over  $3 \lesssim z \lesssim 6$ , when the IGM is known to be ionised. These results reveal that low luminosity galaxies show strong Ly $\alpha$  emission much more frequently than luminous systems, and that at fixed luminosity, the prevalence of strong Lyman- $\alpha$  emission increases moderately with redshift over  $3 < z < 6$ . Based on the striking correlation between blue UV slopes and strong Ly $\alpha$  emitting galaxies in our dataset, we argue that the Ly $\alpha$  fraction trends are governed by redshift and luminosity-dependent variations in the dust obscuration, with likely additional contributions from trends in the kinematics and covering fraction of neutral hydrogen. We find a tentative decrease in the Ly $\alpha$  fraction at  $z \simeq 7$  based on the limited IR spectroscopic data for candidate  $z \simeq 7$  galaxies, a result which, if confirmed with future surveys, would suggest an increase in the neutral fraction by this epoch. Given the abundant supply of  $z$  and Y-drops now available from deep Hubble WFC3/IR surveys, we show it will soon be possible to significantly improve estimates of the Ly $\alpha$  fraction using optical and near-infrared multi-object spectrographs, thereby extending the study conducted in this paper to  $7 \lesssim z \lesssim 8$ .

**Key words:** cosmology: observations - galaxies: evolution - galaxies: formation - galaxies: high-redshift

## 1 INTRODUCTION

Considerable observational progress has been achieved in recent years in the study of star-forming galaxies seen beyond

$z \simeq 3$ , a period corresponding to  $\simeq 2$  Gyr after the Big Bang. It is now clear that this is a period of rapid galaxy evolution and a number of key results have emerged from recent multi-wavelength surveys.

For the colour-selected  $z > 3$  Lyman break galaxies (LBGs), it is now established from various independent sur-

\* dps@ast.cam.ac.uk

veys that the star formation density, deduced from rest-frame UV luminosities, declines monotonically with redshift (e.g. Stanway et al. 2003; Bunker et al. 2004) largely as a result of a corresponding fading of the characteristic UV luminosity (e.g., Ouchi et al. 2004; Yoshida et al. 2006; Bouwens et al. 2006, 2007; McLure et al. 2010). The associated stellar mass density in Lyman break galaxies, deduced from near-infrared Spitzer photometry, increases by  $\simeq 1$  dex from  $z \simeq 6$  to 4 (Eyles et al. 2007; Stark et al. 2009). As the rate of change of stellar mass is governed by ongoing star formation, it is useful to relate the two measures and such a comparison indicates a rapid duty-cycle of star formation activity at this time, unlike the more continuous modes seen for equivalent sources at  $z \simeq 2 - 3$  (Stark et al. 2009). By contrast, the redshift-dependent luminosity function of narrow-band selected *Lyman alpha* emitters, shows no equivalent decline with redshift over  $3 < z < 6$  (Ouchi et al. 2008), suggesting an increasing fraction of line emitters amongst the star forming population at early times. Moreover, detailed studies of the slope of the UV continuum in  $z > 3$  Lyman break galaxies indicates a decreasing dust content at earlier times (e.g. Stanway et al. 2005; Bouwens et al. 2006, 2009b) as well as a luminosity dependence at  $z \simeq 3$  (e.g. Reddy & Steidel 2009). Conceivably the combination of a reduced dust content and a shift to more intense, shorter-term star formation at high redshift, can explain these various redshift-dependent trends.

Notwithstanding this considerable progress, a major concern is that the above conclusions rest largely on deductions made with *photometric data*, particularly for the Lyman break population. Quite apart from the possibility of low redshift interlopers lying within the photometric samples (a problem that increases for drop-out selected samples at redder wavelengths), the wanted physical measures of the star formation rate, dust content and stellar mass are all rendered uncertain by the absence of precise spectroscopic redshifts. While considerable effort has been invested in the spectroscopic study of  $z \simeq 3$  Lyman break galaxies (e.g. Shapley et al. 2003; Steidel et al. 2003; Quider et al. 2010), comparably little spectroscopy has been achieved for higher redshift samples. Steidel et al. (1999) obtained spectroscopic redshifts for nearly 50 bright ( $I < 25$ )  $z \simeq 4$  LBGs. Most surveys of  $z \simeq 5 - 6$   $V$  and  $i'$ -drops have generally involved relatively small samples, typically comprising fewer than 10 sources (e.g. Stanway et al. 2004, 2007; Ando et al. 2007; Dow-Hygelund et al. 2007). Recent deep HST *ACS* Grism observations of the Hubble Ultra Deep Field have allowed the spectra of faint  $z \simeq 5$  LBGs to be characterised (Rhoads et al. 2009), albeit at very low spectral resolution, resulting in 39 redshift confirmations. The largest spectroscopic sample of  $4 < z < 6$  LBGs thus far published is the VLT/FORS2 survey of the Chandra Deep Field South (Vanzella et al. 2002, 2005, 2006, 2008, 2009). This survey represents a major step forward, targetting 195  $B$ ,  $V$  and  $i'$ -drop galaxies and securing high redshifts for 99 of them. In addition, a recent campaign with the VIMOS spectrograph on the VLT has also targeted bright  $z \gtrsim 3.5$  LBGs ( $i'_{775} < 25$ ) in the Chandra Deep Field South, confirming redshifts for 20 bright sources at  $3.5 < z < 5.5$  (Balestra et al. 2010).

We build on these strides in this paper, the first in a series presenting the results of a new Keck survey of  $3 < z < 7$

LBGs selected photometrically in the GOODS fields. The overall goal is to improve our understanding of the evolution of star-forming galaxies during the first 2 Gyr of cosmic history. Fully exploiting the 10 metre Keck aperture, we have designed our survey to target intrinsically fainter sources than those reached in the VLT/FORS2 survey, thereby complementing that effort. Spectroscopy spanning a wide range of intrinsic luminosities is very important if we seek to understand earlier examples of the luminosity-dependent trends seen at  $z \simeq 3$  (Reddy & Steidel 2009). As discussed below, it is equally important to target and study sub-luminous star forming sources at early times, as these may be typical of those galaxies responsible for cosmic reionisation (Bouwens et al. 2007; Ouchi et al. 2009; Bunker et al. 2010; Oesch et al. 2010; McLure et al. 2010).

Understanding evolution in the demographic trends of star-forming galaxies over  $3 < z < 7$  is vital if we are to use galaxies as tracers of *cosmic reionisation*, a cosmic event which is now a frontier of observational cosmology. Knowledge of when reionisation occurred is crucial to our understanding of the nature of the earliest UV-emitting sources as well as the discrepancy between the observed number of dwarf galaxies and those expected from cosmological simulations (e.g. Salvadori & Ferrara 2009). Current observational constraints are limited. WMAP measurements indicate that the universe may have been partially ionised as early as  $z \simeq 11$  (Dunkley et al. 2009; Larson et al. 2010), while observations of transmission in the spectra of quasars reveal that intergalactic hydrogen must be highly ionised below  $z \lesssim 6$ . While the discovery of an accelerated decline and increased variance in the mean transmitted flux from quasars initially led many to suggest that the intergalactic medium (IGM) is still partially neutral at  $z \simeq 6.2$  (Fan et al. 2006), recent work has demonstrated that these results do not necessarily require a sudden change in the ionisation state of the IGM (Becker et al. 2007). Given the difficulty in locating quasars at  $z > 7$ , it seems unlikely that quasar spectroscopy will constrain the epoch when the bulk of the IGM was reionised in the near future.

$\text{Ly}\alpha$  emitting galaxies offer a valuable additional probe of the IGM (e.g., Rhoads & Malhotra 2001; Malhotra & Rhoads 2004; Kashikawa et al. 2006). In principle, the test is straightforward to apply. Young galaxies emit copious amounts of  $\text{Ly}\alpha$  photons, which are resonantly scattered by neutral hydrogen. Hence as we probe the regime when the IGM becomes significantly neutral, the fraction of star-forming galaxies showing strong  $\text{Ly}\alpha$  emission should decrease (e.g. Haiman & Spaans 1999; Santos 2004; Furlanetto et al. 2006; McQuinn et al. 2007; Mesinger & Furlanetto 2008; Iliev et al. 2008; Dayal et al. 2010). Recent measurements of the luminosity function of  $\text{Ly}\alpha$  emitters (LAEs) selected via narrowband imaging have revealed a tantalising decline between  $z = 5.7$  and  $z = 7.0$  (e.g. Kashikawa et al. 2006; Iye et al. 2006; Ota et al. 2008), offering possible evidence that the ionisation state of the IGM evolves over  $6 < z < 7$ .

Regardless of the validity of claims for an increasing fraction of neutral hydrogen over  $6 < z < 7$ , in practice the interpretation of the  $\text{Ly}\alpha$  test is more complex. While the ionisation state of the IGM affects the  $\text{Ly}\alpha$  LF, so does evolution of a multitude of other properties intrinsic to the sampled population (e.g., Verhamme et al.

2006, 2008; Atek et al. 2008). Evolution in the dust content (Bouwens et al. 2009b), the column density, kinematics, and geometrical distribution (generally described as the “covering fraction”) of neutral hydrogen (Shapley et al. 2003; Quider et al. 2009, 2010; Steidel et al. 2010) can each play a key role. Also important for the transmission of Ly $\alpha$  photons is the density of the IGM, which evolves continuously with redshift, and the stellar initial mass function of galaxies, for which few robust constraints exist at high-redshift.

The existence of these complicating factors highlights the importance of understanding how the prevalence of Ly $\alpha$ -emitting galaxies varies just after reionisation in addition to characterising the decline that may occur during reionisation itself. With this goal in mind, we seek to construct an independent measure of the redshift evolution of Ly $\alpha$  emitting galaxies over a large redshift baseline, complementary to past efforts (e.g. Ota et al. 2008). Here we introduce the method of measuring the fraction of strong Ly $\alpha$  emitters (hereafter the “Ly $\alpha$  fraction”) within the LBG population. Applying the Ly $\alpha$  fraction test to a large sample of LBGs has many advantages. Firstly, the LBG samples are already in place over  $4 < z < 8$  owing to deep surveys with HST (e.g. McLure et al. 2010; Bunker et al. 2010; Bouwens et al. 2010b); hence the only time investment required is follow-up spectroscopy. This spectroscopy not only provides a sample of Ly $\alpha$  emitters with known spectroscopic redshifts, but it also provides information on the kinematics of the ISM (e.g. Shapley et al. 2003; Vanzella et al. 2009; Steidel et al. 2010) for individual bright sources (and for faint systems via composite spectra) and improves estimates of dust obscuration via UV colors, both of which are key factors governing the transmission of Ly $\alpha$  photons. By improving our understanding of how these properties change with time, we can begin to isolate the effect of reionization on the evolution in the Ly $\alpha$  fraction. Additionally, the Ly $\alpha$  fraction is insensitive to the declining number density of star-forming galaxies, in contrast to the Ly $\alpha$  luminosity function test (which requires comparison to the UV luminosity function to account for this degeneracy). Naturally, the Ly $\alpha$  fraction test has its own complications, but we show that these can be corrected for (see §3.3 and 3.4), and we thus argue that this test will provide valuable constraints on reionization as new  $7 < z < 10$  LBGs emerge in the next several years.

Our goal is therefore to obtain a robust measure of the luminosity and redshift dependence of the Ly $\alpha$  fraction when the IGM is highly-ionised ( $z \simeq 3 - 6$ ) and to compare it to the Ly $\alpha$  fraction at progressively earlier times. If the IGM ionisation state evolves significantly at  $z \gtrsim 6$  as possibly implied by the narrowband Ly $\alpha$  results, we would expect the measured fraction of LBGs with strong Ly $\alpha$  emission to be lower at  $z \simeq 6 - 8$  than expected from extrapolating the trends seen over  $3 < z < 6$ . By placing the evolution of the Ly $\alpha$  fraction at  $3 < z < 6$  in the context of the evolution of the well-characterised LBG parent population (e.g. variation of dust extinction with redshift and luminosity), we will calibrate the relative importance of factors other than reionisation on the transmission of Ly $\alpha$  photons.

Our Ly $\alpha$  fraction test is ideally suited to our large spectroscopic sample of continuum-selected LBGs spanning the redshift range  $3 \lesssim z \lesssim 7$ . The current Keck sample (including a sample of archival  $i'$ -drops to be presented in Bunker et al. 2010, in preparation) consists of 455 B, V,  $i'$ , and  $z$ -drops

(photometrically-selected to lie at  $3.5 < z < 7.0$ ) spanning a wide range in UV luminosity (to  $M_{UV} \simeq -18$ ). We combine this sample with a more luminous publicly-available FORS2 dataset of 195 sources satisfying photometric criteria similar to those adopted for the Keck surveys. Using this large spectroscopic database, we address the primary goal of this first paper in our series - to compute the Ly $\alpha$  fraction as a function of luminosity and redshift. This will enable us to identify the principal factors governing its evolution over  $3 \lesssim z \lesssim 6$ , prior to extending the test to  $6 \lesssim z \lesssim 8$ , where we can probe changes in the IGM.

The plan of the paper is as follows. In §2, we describe the target selection and spectroscopic observations, and present the rest-frame UV properties of our current sample. In §3, we describe the construction of the Ly $\alpha$  catalog, discuss the method used to measure Ly $\alpha$  equivalent widths, and compute the completeness of Ly $\alpha$  detection as a function of luminosity and redshift. In §4, we discuss the luminosity dependence of Ly $\alpha$  emission in the context of earlier studies at  $z \simeq 3$ . We then turn to the redshift-dependence of Ly $\alpha$  emission and discuss the important implications of our findings. Finally, in §5, we examine the extant data on the rate of occurrence of Ly $\alpha$  emission for candidate sources thought to lie beyond  $z \simeq 6$ . We use this to test the practicality of using our test as a valuable probe of cosmic reionisation. We summarise the conclusions of our study in §6.

Throughout the paper, we adopt a  $\Lambda$ -dominated, flat universe with  $\Omega_{\Lambda} = 0.7$ ,  $\Omega_M = 0.3$  and  $H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$ . All magnitudes in this paper are quoted in the AB system (Oke & Gunn 1983).

## 2 OBSERVATIONS

We present the results of a new and ongoing Keck spectroscopic survey of photometrically-selected  $B$ ,  $V$  and  $i'$ -band ‘dropouts’ in the northern and southern GOODS fields (Giavalisco et al. 2004b). The GOODS fields were selected for this survey on account of the depth and precision of their unique multi-color photometric data useful for selecting targets, as well as the availability of associated Spitzer and Chandra data which provided valuable stellar masses and AGN-related properties (Eyles et al. 2005; Yan et al. 2006; Eyles et al. 2007; Stark et al. 2007a, 2009; González et al. 2010; Labbé et al. 2009).

### 2.1 The Keck/DEIMOS Survey in GOODS-N and GOODS-S

The majority of spectra discussed in this paper were obtained from an ongoing survey undertaken with the DEep Imaging Multi-Object Spectrograph (DEIMOS) at the Nasmyth focus of the 10 m Keck II telescope (Faber et al. 2003). DEIMOS is comprised of eight 2k x 4k CCDs spanning roughly half of the ACS GOODS field of view ( $\simeq 16'.7 \times 5'.0$ ) on the sky. Our first observations have primarily focused on targeting the  $B$  and  $V$ -drop populations. Although future DEIMOS observations will expand coverage of higher redshift  $i'$  and  $z$ -band dropouts, we include early data taken in this territory, some of which is described independently in Bunker et al (2010, in preparation).

The recently-studied target list is primarily selected

from the  $B$ ,  $V$  and  $i'$  dropout samples discussed in Stark et al. (2009). To this we will add earlier Keck data on  $i'$  drops discussed in §2.2 (Bunker et al. 2003; Stanway et al. 2004, Bunker et al. 2010, in preparation) as well as newly-discovered  $z$ -drops from the recent WFC3/IR UDF campaign (see below). Optical magnitudes range from relatively bright systems ( $z_{850} \simeq 23.5$ ) to the faintest dropouts observed in GOODS ( $z_{850} \simeq 27.5$ ). Although the ACS photometry in Stark et al. (2009) was based upon the GOODS version r1.1 ACS multi-band source catalogs, for this analysis we have updated the photometry to the recently released GOODS version 2.0 catalogs. These new catalogs contain significantly deeper  $z_{850}$ -band imaging. The  $5\sigma$  limiting magnitudes vary across the different frames, but are typically 28.0 in F435W ( $B_{435}$ ), 28.2 in F606W ( $V_{606}$ ), 27.9 in F775W ( $i'_{775}$ ), and 27.8 in F850LP ( $z_{850}$ ) when measured in 0.5 arcsecond diameter apertures. At the median redshifts expected for these populations ( $z = 3.8$  for B-drops,  $z = 5.0$  for V-drops, and  $z = 5.9$  for  $i'$ -drops, e.g., Bouwens et al. 2007), these limits correspond to absolute magnitude limits of  $M_{UV} \simeq -18.2$ ,  $-18.8$ , and  $-19.1$  for B, V, and  $i'$ -drops.

A summary of the various observing campaigns is given in Table 1. Apart from the  $i'$ -drop exploratory survey discussed by Bunker et al. 2010, (in preparation), in our campaigns during 2004-2007 targets were selected to fill empty regions on slitmasks designed for other purposes, e.g., studying the kinematics of disk galaxies at  $z \simeq 1$  (MacArthur et al. 2008). For these observing runs, we used the Gold 1200 line  $\text{mm}^{-1}$  grating which provided coverage between 5570 and 8210 Å (allowing  $\text{Ly}\alpha$  to be detected in the redshift range  $z = 3.6$  to 5.8), with a spectral pixel size of  $0.3 \text{ Å pixel}^{-1}$ . The spectral resolution measured from skylines was  $1.4 \text{ Å}$ .

The main survey began in earnest in 2008, when we started a dedicated programme geared at obtaining spectra of  $z > 3$  dropouts. Most spectra were obtained from 5 slitmasks observed in April 2008 and March 2009 (Table 1). These slitmasks utilised the 600 line  $\text{mm}^{-1}$  grating on DEIMOS, providing spectroscopic coverage between 4850 Å and 10150 Å (allowing  $\text{Ly}\alpha$  to be detected between  $z \simeq 3.0$  and 7.3) with a spectral pixel scale of  $0.7 \text{ Å pixel}^{-1}$ . These spectra provided a resolution (measured from skylines) of  $\simeq 3.5 \text{ Å}$ . This setup allowed us to efficiently follow-up B and V-band dropouts simultaneously. Each individual mask was observed for  $\simeq 5 - 7$  hours and contained  $\simeq 80$ -110 dropouts. Seeing was typically  $0''.8$ , ranging between  $0''.5$  and  $1''.0$ .

We observed a final slitmask toward GOODS-S on 19-20 October 2009. For this run, we prioritised  $i'$ -drops and newly-discovered  $z$ -drops (Oesch et al. 2010; McLure et al. 2010; Bunker et al. 2010; Wilkins et al. 2010a) and therefore opted for the higher resolution 830 line  $\text{mm}^{-1}$  grating blazed at 8640 Å with order blocking filter OG550. With this set-up, the spectra generally provide coverage between 6800 and 10100 Å (allowing  $\text{Ly}\alpha$  to in principle be detected between  $z=4.5$  and 7.3), with each spectral pixel spanning  $0.46 \text{ Å}$ . Skylines are measured to have a FWHM of  $\simeq 2.4 \text{ Å}$ , a significant improvement upon the resolution obtained with the 600 line grating. However, poor seeing (average of 1.3 arcseconds) and fog made redshift confirmation particularly difficult.

All data were reduced using the spec2d IDL pipeline de-

veloped for the DEEP2 Survey. The final reduction provides two-dimensional (2D) spectra and variance arrays, along with a one-dimensional (1D) extraction at the expected position of the dropout. Wavelength calibration was typically obtained from Ne+Xe+Cd+HG+Zn reference arc lamps. In general, the final wavelength solution is accurate to within  $\simeq 0.1 \text{ Å}$ . Examples of reduced 1D-spectra are presented in Figure 1.

We flux calibrated the spectra using spectroscopic standard stars observed in the 24-26 March 2009 observing run. We tested the flux calibration derived from these standards using spectra of alignment stars included on the slitmask (observed in  $2 \text{ arcsec} \times 2 \text{ arcsec}$  boxes). We compute optical broadband magnitudes for the alignment stars from the flux-calibrated spectra using the appropriate filter transmission functions. The magnitudes measured from the spectra match those from the ACS images to within a factor of  $\simeq 2$ . We bootstrapped a flux calibration on spectra from observing runs for which spectroscopic flux standards were not taken (03-05 April 2008) using the measured flux in alignment stars that are in common between the 2008 and 2009 observing runs.

Using the flux calibrations, we compute our typical  $1\sigma$  flux sensitivity across the DEIMOS spectra for the 600 line grating. These measurements predict that we should detect continuum at the  $1\sigma$  level for sources with  $V \simeq 25.5$  (per spectral resolution element in 1D spectra which have been extracted over  $\simeq 1''$ ) across much of the wavelength regime covered by the 600 line spectra. This prediction is consistent with expectations based on the optical magnitudes of sources that show continuum traces in the spectra. The average  $10\sigma$  limiting line flux is  $1\text{--}1.5 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  between 6500 Å and 9300 Å, although sky lines become much more common toward the red side of the spectra. In a later section, we present more detailed simulations that reveal the completeness for emission lines of a given flux and redshift.

For the most recent run (October 2009), the limiting sensitivity was significantly worse than in previous runs due to the seeing and fog. Based on the signal obtained from the bright alignment stars on the mask (each of which has known broadband magnitudes) and the signal from our spectroscopic standard stars, we estimate that our continuum  $1\sigma$  sensitivity (computed per resolution element with a spatial extraction width of  $\simeq 1.5''$ ) was  $\simeq 3.5\text{--}4.0 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$  in between sky lines (corresponding to a continuum magnitude of  $i' \simeq 24.25$ ). Assuming typical line widths, this limit translates into a  $10\sigma$  line flux limit of  $2.5\text{--}4.0 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  for  $\text{Ly}\alpha$ . As most of the sources targeted in this run were faint ( $z_{850} > 26$  for the  $i'$ -drops), this means that we are only sensitive to very strong emission lines (the  $10\sigma$  rest-frame equivalent width limit is  $\simeq 75\text{--}100 \text{ Å}$  for sources with  $z_{850} \simeq 26.5$ ). For fainter sources (e.g. the majority of WFC3  $z$ -drops in the UDF), the equivalent width limits are too large to enable detection of  $\text{Ly}\alpha$ .

To summarise the current status of our DEIMOS observations, we have obtained 549 spectra of B, V,  $i'$ , and  $z$ -drops. To boost the S/N of our spectra, many dropouts were observed on multiple masks; hence, each spectra does not correspond to a unique sources. Accounting for this, we observed a total of 268 B-drops, 95 V-drops, 19  $i'$ -drops, and 17  $z$ -drops. We combine this sample with archival Keck and VLT spectra in the following two subsections, and in

Number	Field	Mask ID	Date	$t_{\text{exp}}$ (ksec)	$N_B$	$N_V$	$N_i$	$N_Z$	Grating
1	GOODS-S	GS031	08-09 January 2003	19.8	0	0	3	0	1200
2	GOODS-N	GN031	02-06 April 2003	37.8	0	0	5	0	1200
3	GOODS-S	GS041	11 December 2004	21.9	0	0	20	0	1200
4	GOODS-S	GS051	31 October, 01-02 November 2005	8.4	0	0	17	0	1200
5	GOODS-S	GS071	10-11 November 2007	18.0	7	7	0	0	1200
6	GOODS-N	GN081	03-05 April 2008	21.6	85	9	0	0	600
7	GOODS-N	GN082	03-05 April 2008	21.6	95	12	0	0	600
8	GOODS-N	GN083	03-05 April 2008	20.4	86	14	0	0	600
9	GOODS-N	GN094	24-26 March 2009	18.0	45	63	0	0	600
10	GOODS-N	GN095	24-26 March 2009	25.2	43	36	0	0	600
11	GOODS-S	GS091	19 October 2009	19.2	0	0	19	17	830
Total Unique Keck/DEIMOS Sample					268	95	64	17	—
Total Unique VLT/FORS2 Sample					83	56	56	0	—
Combined Unique Sample					351	151	108	17	

**Table 1.** Summary of observations with Keck/DEIMOS and VLT/FORS2.  $N_B$ ,  $N_V$ ,  $N_i$ ,  $N_Z$  denote the number of B, V,  $i'$ , and  $z$ -drops observed on each mask. To maximise S/N, many sources were observed on multiple DEIMOS masks; we account for such duplication when computing the total Keck sample size. The  $i'$ -drops in the first two rows were originally published in Bunker et al. (2003) and Stanway et al. (2004), and the  $i'$ -drops presented in rows 3 and 4 are from Bunker et al. (2010, in preparation). The VLT FORS2 sample is taken from observations presented in Vanzella et al. (2009). The combined total sample in the last row includes all unique dropouts in the Keck and VLT surveys.

§2.4, we present the absolute magnitude distribution of the combined VLT and Keck spectroscopic samples.

## 2.2 Archival Keck Spectroscopy in GOODS-N/S

Additional  $i'$ -drops were observed with Keck/DEIMOS between 2003 and 2005 (Table 1). Early observations were presented by Bunker et al. (2003) and Stanway et al. (2004), and an updated discussion, including additional DEIMOS observations from 2003-2005, is given by Bunker et al. (2010). These sources were observed with the 1200 line  $\text{mm}^{-1}$  (described above) with seeing of  $0''.7 - 1''.0$ .

In total, 45  $i'$ -drops were observed in the two GOODS fields on 4 separate slitmasks. Of the 45 sources observed, 12 were included in the Vanzella et al. (2009) VLT/FORS observations discussed below. Integration times ranged between 2.3 and 10.5 hrs. The  $z_{850}$ -band magnitudes of the sources ranged between 24.7 and 28.3. Given the considerable range of exposure times, we take care to estimate the equivalent width completeness for sources of different magnitudes on the various masks that were observed.

## 2.3 Archival VLT/FORS Spectroscopy in GOODS-S

Two programmes aimed at following up high-redshift dropouts in GOODS-S have been conducted with the VLT. The first of these used the FORS2 multi-object spectrograph (Vanzella et al. 2005, 2006, 2008, 2009), and the second used the VIMOS multi-object spectrograph Balestra et al. (2010). Both teams have released their datasets to the public. In this paper, we focus on the FORS2 survey, as its survey characteristics (resolution, spectral coverage) are closest to the DEIMOS survey. We discuss the basic FORS2 survey details below.

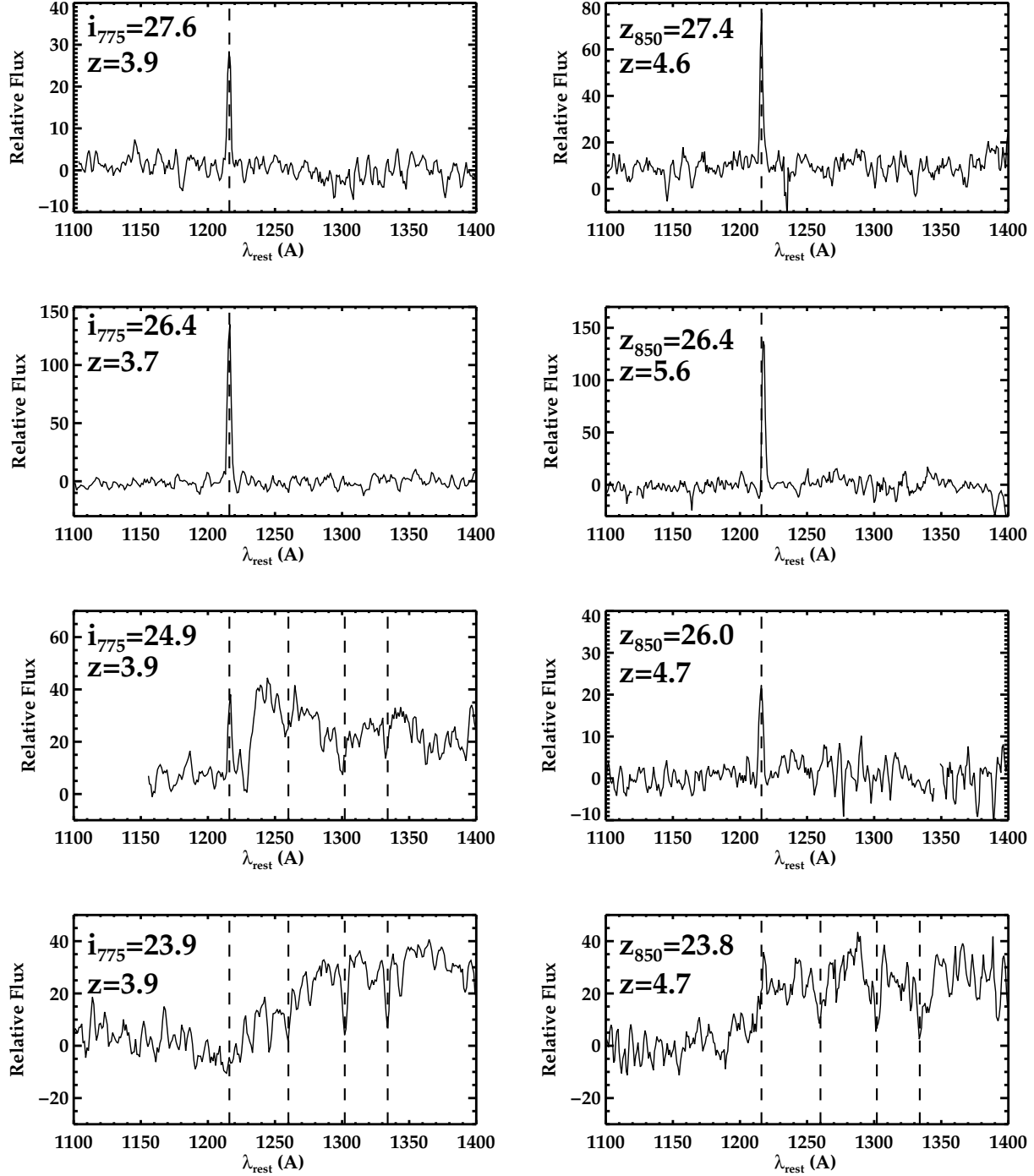
Between September 2002 and October 2006, the VLT FORS2 multi-object spectrograph was used to observe

sources identified in the GOODS imaging of CDF-S. In total, 38 FORS2 masks were obtained using the 300I grism without an order-separating filter. Each mask was observed for roughly 4-6 hours. In general, the spectra provide coverage between 6000 Å and 10000 Å, with a spectral resolving power of  $R=660$  which provides resolution of  $\simeq 13$  Å at 8600 Å.

The FORS2 database provides redshift classifications and quality grades (ranging from A to C) for the entire spectroscopic sample. The colour criteria used to select the dropouts in the FORS2 sample are discussed in Giavalisco et al. (2004a); however, for the B-drops, a slight variation in the colour-selection was adopted (for details see Vanzella et al. 2009).

In general, these criteria are very similar to those we have adopted for our DEIMOS survey. Using the coordinates provided in the public FORS2 database, we query the version 2.0 ACS catalogs for GOODS-S and measure optical magnitudes in an identical fashion as described in §2.1. Adopting the selection criteria used for the DEIMOS sample (see Stark et al. 2009), we find 83 B-drops, 56 V-drops, and 56  $i'$ -drops that were observed with FORS2. Redshifts were obtained for 48 B-drops (46 with  $z > 3$ ), 37 V-drops (32 with  $z > 4$ ), and 26  $i'$ -drops (21 with  $z > 5$ ).

The magnitude distribution of the FORS2 sample is generally weighted toward brighter sources, with few B and V-drops with magnitudes fainter than  $z_{850} \simeq 26$ . Given the inherent faintness of  $i'$ -drop samples, the magnitude distribution is significantly fainter than for the lower redshift dropout samples, with  $z_{850} \simeq 25 - 27$ . In Figure 2, we plot a comparison of the absolute magnitude distribution of the FORS2 and DEIMOS dropout samples. The current DEIMOS sample contributes 76% of the B-drops and 63% of the V-drops and crucially extends the spectroscopic coverage to lower luminosities.

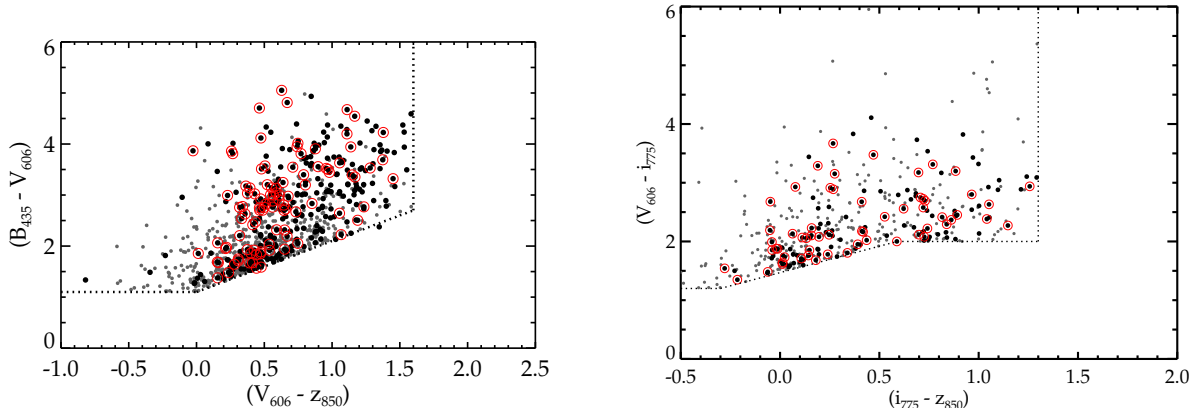


**Figure 1.** Montage of DEIMOS 1D spectra from our survey arranged according to redshift and luminosity. B-drops are shown in the left column, and V-drops appear in the right column. Each panel contains a label indicating the apparent magnitude of the continuum and redshift. Spectra are smoothed to a spectral pixel size of  $\simeq 3 \text{ \AA}$ . Where present, dashed vertical lines denote Ly $\alpha$ , Si II 1260, OI+SiII 1303, and CII 1334 lines.

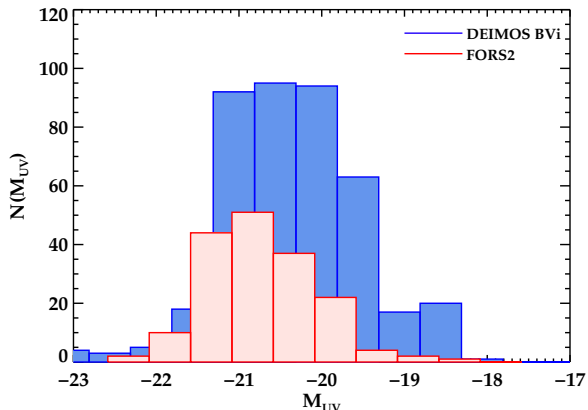
## 2.4 Final Spectroscopic Sample

When combined, the FORS2 and DEIMOS surveys contain a total of 627 spectra of unique high-redshift dropouts (351 B-drops, 151 V-drops, 108  $i'$ -drops, and 17  $z$ -drops). In Figure 3, we present colour-colour diagrams of the entire B

and V-drop spectroscopic sample, indicating the selection criteria. The  $i'$ -drops were selected using the standard single  $i' - z > 1.3$  colour criterion (see Figure 4). Comparing the distribution of selected targets on these figures with the larger sample of sources in the Stark et al. (2009) photometric catalog, we demonstrate that the colours of our targets



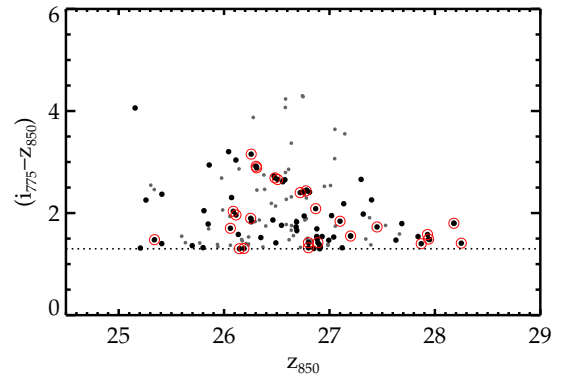
**Figure 3.** Colour-colour diagrams for the B-drops (left) and V-drops in combined VLT and Keck spectroscopic surveys. Objects with  $\text{Ly}\alpha$  in emission are denoted with a second red circle. The dotted lines show the Lyman break selection criteria adopted in this paper. The small grey circles show the distribution of colours for the parent population of LBGs from Stark et al. (2009).



**Figure 2.** Absolute magnitude distribution of FORS and DEIMOS spectroscopic samples. The new DEIMOS B, V, and  $i'$ -drops are shown in shaded blue, and below the FORS2 observations (Vanzella et al. 2009) are shown in light red. The DEIMOS datasets comprise the majority of the spectra considered in our analysis.

with spectroscopic coverage span nearly the full range of the parent LBG population.

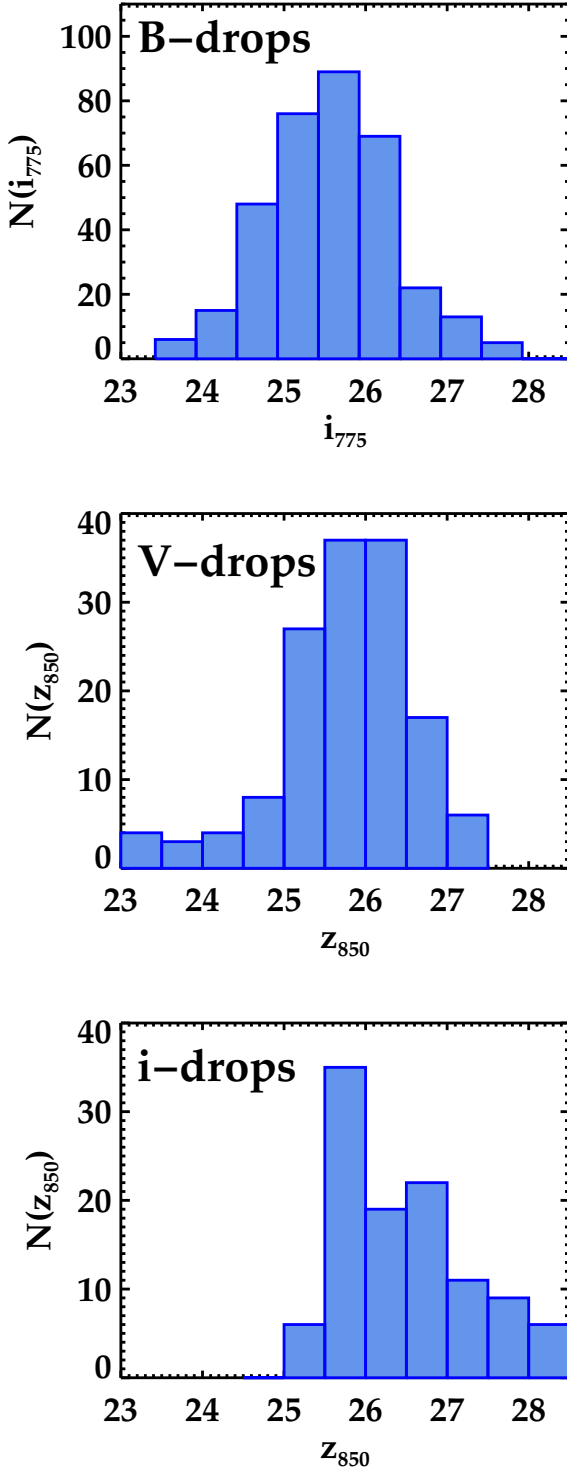
Figure 5 also shows the apparent magnitude distributions of the various dropout samples. While previous surveys have focused on sources with apparent magnitudes brighter than  $m \simeq 26$ , a major achievement of our survey is that we have been able to push significantly below this limit with DEIMOS. Our primary motivation for doing so is that the characteristic UV luminosity shifts to lower values at higher redshifts (e.g., Bouwens et al 2007), so to compare source properties over  $3 \lesssim z \lesssim 7$  in a meaningful manner, probing deep becomes a necessity. To demonstrate our survey has achieved this over  $3 < z < 6$ , in Figure 6, we compare the absolute magnitude distribution of our various dropout samples. Current estimates of the characteristic absolute magnitude at  $z \simeq 7$  are  $M_{\text{UV}} \simeq -19.9$  (Bouwens et al. 2009a; Ouchi et al. 2009; Oesch et al. 2010). As objects more lumi-



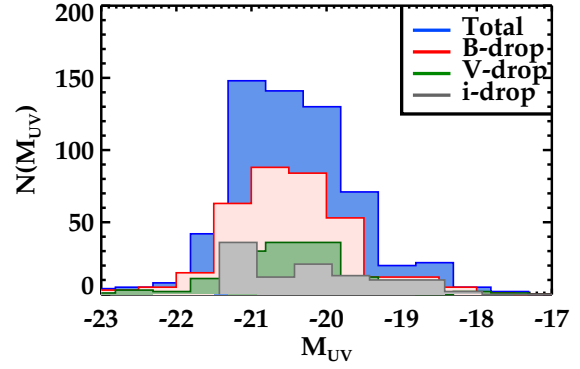
**Figure 4.**  $i' - z$  colour versus magnitude for  $i'$ -drops with spectroscopic observations with the dashed line showing the selection cut. Points surrounded by a red open circle indicates sources with  $\text{Ly}\alpha$  seen in emission, and the small grey circles indicate the colours and magnitudes of  $i'$ -drops from the parent LBG samples (Stark et al. 2009).

nous than this are exceedingly rare at  $z \gtrsim 6 - 7$ , if we are to make consistent  $\text{Ly}\alpha$  fraction comparisons, we must probe to at least this depth over  $4 < z < 6$ .

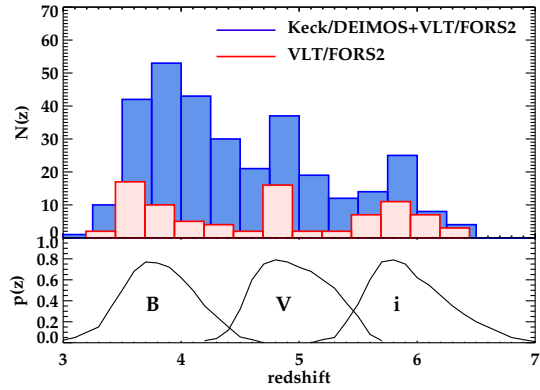
Redshifts were determined via visual examination of the spectra (see Figure 7 for a redshift distribution). For UV faint sources, the continuum is too faint for identification of the Lyman break or absorption lines, so we can only measure spectroscopic redshifts for those sources with  $\text{Ly}\alpha$  in emission. For UV bright sources, redshift identification is performed via a combination of the Lyman break, interstellar absorption lines, and/or  $\text{Ly}\alpha$  emission. We classify all redshifts according to their quality, ranging from A (definite), B (secure), C (possible/likely). Nearly all  $\text{Ly}\alpha$  emitters fall into the first two categories owing to the combination of line profile, lack of other emission lines, and strong continuum break (in spectra and/or imaging), but some of the absorption line detections are much more tenuous owing to sky line residuals and noise. As the results of this paper are in-



**Figure 5.** Distribution of apparent magnitudes of B-drops (top), V-drops (middle), and  $i'$ -drops (bottom) in combined Keck and VLT spectroscopic survey.



**Figure 6.** Distribution of absolute magnitudes of sources in the combined DEIMOS and FORS2 spectroscopic survey (shaded blue). The shaded light red, green, and grey denote the magnitude distribution of the B, V, and  $i'$ -drop samples.



**Figure 7.** Redshift distribution of B, V, and  $i'$ -drops with spectroscopic confirmation in GOODS-N and GOODS-S (dark blue). This sample includes absorption line systems in addition to the Ly $\alpha$  emitters discussed in this paper. The total sample contains 179 galaxies with redshifts in the range  $3 \lesssim z \lesssim 4.5$ , 87 galaxies with redshifts over  $4.5 \lesssim z \lesssim 5.5$ , and 44 galaxies with redshifts over  $5.5 \lesssim z \lesssim 6.5$ . For reference, we display the redshift distribution of the VLT/FORS2 survey (Vanzella et al. 2009) in light red.

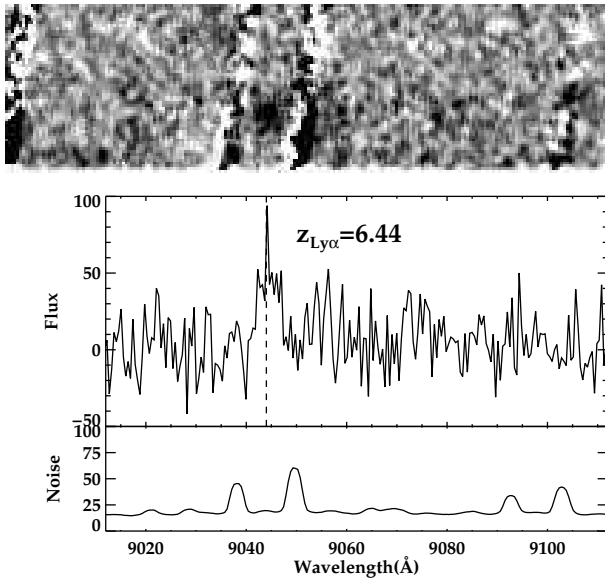
dependent of the absorption line sample, we delay further discussion of the absorption line catalog until a subsequent paper (Stark et al. 2010, in preparation), while details of the Ly $\alpha$  selection are described in the following section. However, we note that, in total, the FORS2+DEIMOS sample contains 179 redshifts over  $3 \lesssim z \lesssim 4.5$ , 87 redshifts over  $4.5 \lesssim z \lesssim 5.5$ , and 44 redshifts over  $5.5 \lesssim z \lesssim 6.5$ .

### 3 EMISSION LINE MEASUREMENTS

#### 3.1 Constructing the Ly $\alpha$ catalog

Emission lines were initially identified visually in the two-dimensional DEIMOS spectra and later in the one-dimension extractions at the position of the dropouts. We took care to distinguish Ly $\alpha$  from other emission features





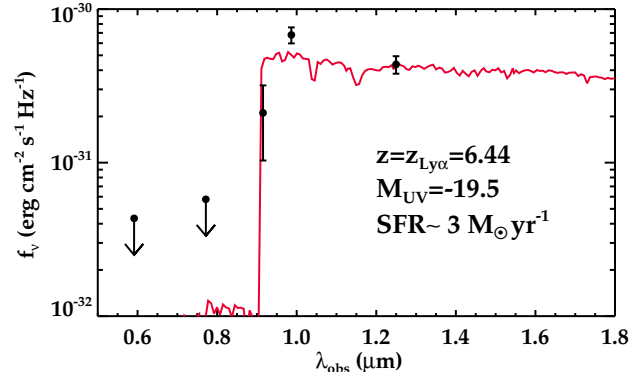
**Figure 8.** Spectra of a  $J_{125} \simeq 27.3$   $z$ -drop showing tentative Ly $\alpha$  emission at 9044 Å. *Top panel:* The 2D spectrum shows a significant emission feature detected at the  $7\sigma$  level (black corresponds to positive flux in the image) in between two sky lines and centered exactly at the position of  $z$ -drop ‘3’ in Wilkins et al. (2010a). *Bottom panel:* The 1d spectrum of the galaxy and associated noise. The spectrum and noise are not smoothed to avoid blending with skylines at 9038 Å and 9048 Å. The emission line between these features lies in a region of low noise, spanning  $\simeq 10$  Å in width.

(e.g. [OII] which is resolved by DEIMOS) which correspond to lower-redshift galaxies. Ly $\alpha$  emission is detected in 152 of the DEIMOS dropouts.

For the VLT/FORS dataset, the redshifts were determined in Vanzella et al. (2009). As discussed in §2.3, to ensure a uniform selection across the Keck and VLT samples, we performed our own photometric selection. With the resulting subset of 193 galaxies, we identified those objects showing Ly $\alpha$  in emission in their one-dimensional spectra.

We defined Ly $\alpha$  redshifts ( $z_{Ly\alpha}$ ) for each object as the wavelength at which the Ly $\alpha$  line is at its peak flux value. As Ly $\alpha$  is generally redshifted by at least  $\simeq 300$  km s $^{-1}$  from the frame of rest of the galaxy (e.g. Shapley et al. 2003; Vanzella et al. 2009), we note that this redshift is not necessarily equivalent to the systemic redshift of the galaxy. Across both surveys, we identified Ly $\alpha$  emission in 108 B-drops, 63 V-drops, and 28  $i'$ -drops. The relative colour distribution of these sources in relation to the larger spectroscopically-targeted sample is shown in Figures 3 and 4.

In addition to the B, V, and  $i'$ -drops, we present tentative spectroscopic confirmation for one of the  $z$ -drops that was studied in poor conditions in the October 2009 DEIMOS run (Table 1). The only  $z$ -drop to show a clear emission feature at the expected object location was source 3 in Wilkins et al. (2010a). This object, identified in the GOODS ERS WFC3 imaging of CDF-S (PI: O’Connell), is reasonably faint ( $J_{125} \simeq 27.3$ ) but is brighter than most of the  $z \gtrsim 6$  sources detected in the UDF (e.g. Oesch et al. 2010; Bunker et al. 2010; McLure et al. 2010). The DEIMOS spec-



**Figure 9.** Spectral energy distribution of  $z$ -drop ‘3’ from Wilkins et al. (2010a). The datapoints show detections and upper limits from ACS and WFC3 imaging of CDF-S. Overplotted is a Bruzual-Charlot population synthesis model with a redshift fixed at  $z = 6.44$ , the spectroscopic redshift inferred from the emission line detected in Figure 8. The broadband imaging data show a prominent break where the Lyman break is predicted and a significant excess of flux in the medium-band  $Y_{098}$  filter (relative to the  $J_{125}$ -band), as expected in the presence of strong Ly $\alpha$  emission.

trum illustrates a significant  $7\sigma$  emission line in between sky lines and centered at 9044 Å (Figure 8). The S/N and nearby sky line do not enable a robust measure of the asymmetry of the line. The broadband SED is well fit by a source  $z \simeq 6.44$  with strong Ly $\alpha$  contaminating the medium-band  $Y_{098}$  filter (Figure 9). If this emission feature is Ly $\alpha$ , it would lie at  $z = 6.44$ , consistent with the photometric redshift predictions. Our flux calibration suggests a flux of  $1.5 \times 10^{-17}$  erg cm $^{-2}$  s $^{-1}$  and hence an equivalent width (rest-frame) of 83 Å. We will confirm the redshift of this source in future campaigns of CDF-S.

### 3.2 Computation of Ly $\alpha$ properties

Next we compute the flux ( $F_{Ly\alpha}$ ) and equivalent width ( $W_{Ly\alpha}$ ) for each Ly $\alpha$  emitter in our spectroscopic sample. Previous attempts to constrain evolution in the prevalence of Ly $\alpha$  emitters have focused on measuring evolution in the luminosity function of Ly $\alpha$  emitters (selected via narrow-band filters). For our Ly $\alpha$  fraction test described in §1, we are interested in determining the percentage of LBGs of a given luminosity with Ly $\alpha$  emission much stronger than the continuum flux. This test thus relies on accurate measurements of the Ly $\alpha$  equivalent widths ( $W_{Ly\alpha}$ ).

In principle,  $W_{Ly\alpha}$  provides a more robust constraint than  $F_{Ly\alpha}$  as it does not rely on an absolute flux calibration. However since the majority of spectra in our sample have broadband continuum magnitudes fainter than the  $1\sigma$  continuum flux limit of our survey ( $m \simeq 25 - 26$ , §2.1), we can only place an upper limit on the continuum flux measured in this subset of our spectra, thus producing a lower limit to the observed  $W_{Ly\alpha}$ . We can obtain a better estimate of the equivalent width by adopting the continuum flux measured from broadband imaging, taking care to avoid filters that are contaminated by Ly $\alpha$ . We detail the specific procedure used to measure  $W_{Ly\alpha}$  below.

For each spectrum, we compute the line flux,  $F_{Ly\alpha}$ , by summing emission in excess of the continuum between 1213 and 1221 Å, taking care to avoid contribution from nearby sky lines or artifacts and ensuring that the spatial extraction box covers the entire spatial width of the line emission.

The measurement of the continuum flux depends on whether or not continuum is detected. For those objects with continuum detections, we compute the average continuum level redward of  $Ly\alpha$ ,  $c_{red}$ , by averaging the flux in regions between OH sky lines between 1225 Å and 1255 Å in the rest-frame of the galaxy. As discussed in Kornei et al. (2009), this should minimize contribution from nearby absorption features. The observed-frame  $W_{Ly\alpha}$  is then computed by taking the ratio of  $F_{Ly\alpha}$  and  $c_{red}$ .

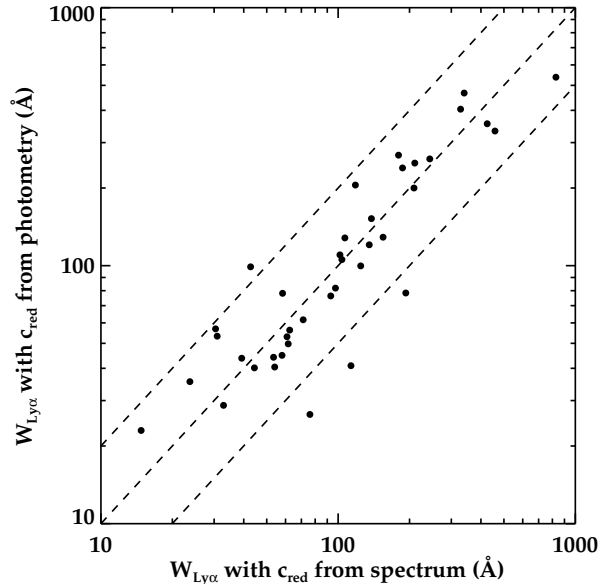
For those objects without continuum detections, we compute equivalent widths using the continuum level just redward of  $Ly\alpha$  with the broadband photometry discussed in the previous section and taking care not to include the contribution of  $Ly\alpha$  to the continuum. For the B-drops and V-drops, we use the  $i'_{775}$  and  $z_{850}$ -band fluxes, respectively. These measurements provide the luminosity at rest-frame  $\simeq 1500$  Å, rather than just redward of  $Ly\alpha$ . The vast majority of sources are very blue (and hence nearly flat in  $f_\nu$ ), requiring no correction between the flux at 1500 Å and that at 1240 Å (the central value in the wavelength-region summed for continuum measurements above). For those few sources with very red UV slopes (measured from the broadband SEDs presented in Stark et al. 2009), we apply a small adjustment to correct for the change in flux between 1500 Å and 1240 Å.

For galaxies with redshifts above  $z \simeq 5.7$ , the  $z_{850}$ -band filter is contaminated by both  $Ly\alpha$  emission, if emission is present, as well as  $Ly\alpha$  forest absorption shortward of rest 1216 Å. Accurate continuum determinations must account for this. If sources contain Y or J-band detections via WFC3 or ISAAC, then we use these measures for the UV continuum. However, at the moment, the majority of UV-faint  $i'$ -drops are not detected with significance in the near-IR, so we must use  $z_{850}$  detections for these sources. For galaxies with no detected  $Ly\alpha$  emission, we must only correct for the  $Ly\alpha$  forest absorption, which we do assuming the redshift is identical to its value inferred from BPZ and that its SED is flat in  $f_\nu$ . Corrections range from  $\simeq 0.2$  mag at  $z = 6$  to 0.7 mag at  $z \simeq 6.4$ . But for  $z > 5.7$  objects with strong  $Ly\alpha$  emission, we also subtract off the line contribution when computing the continuum flux. Typical line contributions are  $\simeq 0.1$ -0.3 mag.

To test the reliability of the above method, we examine the subset of galaxies with bright UV-continua, comparing the continuum flux determined from broadband-imaging to that extracted from the spectra. We find that the median fractional error using the estimate from broadband imaging is  $\simeq 20\%$  (Figure 10). We add this error in quadrature to the photometric error on each equivalent width measurement.

### 3.3 Completeness of $Ly\alpha$ detection

In order to properly assess the fraction of  $Ly\alpha$  emitters in our sample as a function of UV luminosity and redshift, we must consider how completeness varies with apparent magnitude and wavelength of the  $Ly\alpha$  emission line. We estimate the typical completeness by adding fake  $Ly\alpha$  emission to random

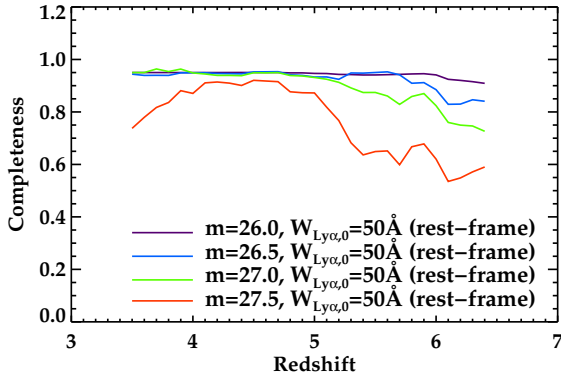


**Figure 10.** Reliability of  $W_{Ly\alpha}$  measurements. The x-axis shows equivalent widths (observed-frame) determined directly from spectra for sources bright enough for a continuum measurement. The y-axis shows the equivalent widths measured for the same sources using the continuum flux from the broadband photometry. The dashed lines demarcate values  $0.5\times$  and  $2\times$  the  $W_{Ly\alpha}$  measured directly from the spectrum. The median fractional error from using equivalent widths derived using the continuum flux from broadband imaging is  $\simeq 20\%$ .

positions across the DEIMOS and FORS2 spectra. In each case, we measure the line properties ( $W_{Ly\alpha}$ ,  $F_{Ly\alpha}$ ,  $S/N$ ) of the fake emission feature. We ran enough trials (using a large number of spectra from each mask) to obtain reliable estimates of the completeness of the  $Ly\alpha$  recovery.

Our goal is to identify a lower flux threshold above which  $Ly\alpha$  is highly complete for most objects in our sample in order to minimize the necessary completeness corrections. We illustrate the results of the completeness simulations for the 600 line  $\text{mm}^{-1}$  grating on DEIMOS in Figure 11. The masks on this grating included B and V-drops which span the redshift range  $3.5 \lesssim z \lesssim 5.5$ . The simulations reveal that sources with  $m_{AB} \simeq 27.0$  and with rest-frame  $Ly\alpha$  equivalent widths ( $W_{Ly\alpha,0}$ ) in excess of 50 Å are generally recovered over nearly the entire redshift range probed by our dropouts (see Figure 11). The high completeness for very strong  $Ly\alpha$  emitters amongst bright sources ( $m \lesssim 26$ ) arises as these bright emission features correspond to fluxes that are in excess of  $10$ - $20\sigma$  and are recovered even when they lie on top of sky lines. The  $W_{Ly\alpha,0} > 50$  Å emission line completeness begins to decline for very faint sources ( $i' \simeq 27.5$ ) at the high- $z$  tail of the V-drop redshift distribution. For the FORS2 data, the spectra show similarly high completeness for B and V-drops with  $W_{Ly\alpha,0} > 50$  Å. These simulations suggest that the measured  $Ly\alpha$  fraction of sources in the redshift range  $3.5 \lesssim z \lesssim 5.5$  should not suffer from significant incompleteness for B and V-drops more luminous than  $M_{UV} \simeq -19$ .

For the  $i'$ -drops, the completeness in the deep DEIMOS and FORS2 spectra remains high for strong (e.g.  $W_{Ly\alpha,0} >$



**Figure 11.** Emission line recovery completeness. The completeness is determined via simulations placing fake lines in spectra and testing the rate at which sources about the equivalent width threshold are recovered. From top to bottom, the figure shows completeness versus redshift for  $W_{\text{Ly}\alpha,0}$  sources with continuum magnitudes (longward of the Lyman break) of 26.0, 26.5, 27.0, and 27.5.

50 Å) Ly $\alpha$  lines. However, it is clear from Figure 11 that incompleteness is not negligible, particularly for faint ( $z_{850} > 27.0$ ) sources at  $z \gtrsim 5.8$  which are less than 80% complete. We thus adopt this as our  $i'$ -drop magnitude threshold for inclusion into the Ly $\alpha$  fraction test, limiting us to sources more luminous than  $M_{\text{UV}} \simeq -19.7$ . We also do not include the 17  $i'$ -drops on the mask GS051 (see Table 1) from Bunker et al. 2010 (in preparation) owing to its reduced integration time of 2.3 hours.

### 3.4 Contamination in spectroscopic samples

Although foreground emission line sources (e.g. [O II] emitters can be readily distinguished from those revealing Ly $\alpha$  (§3.1), our Ly $\alpha$  fraction test requires that we have a reliable sample of LBGs for which no emission line is seen.

While the Lyman break selection criteria are chosen to minimize the inclusion of low-redshift and stellar contaminants, it is clear that interlopers still populate dropout samples. For our purposes, it is important that we consider the luminosity and redshift dependence of contaminants, as these could create artificial trends in our derived Ly $\alpha$  fractions. We expect low- $z$  contamination to increase toward the fainter end of our sample. This is primarily due to photometric scatter; since faint sources are detected with lower S/N and have less dynamic range available to constrain the break, it is more likely that a faint low- $z$  source will be scattered into the LBG selection window. However, if the typical contamination is fairly low in all luminosity bins (e.g.  $\lesssim 10\%$ ), then this would only require a minor correction to the luminosity dependence of the Ly $\alpha$  fraction.

To investigate this in more detail, we compute photometric redshift probability distributions for the spectroscopic sample using the observed photometric catalogues compiled in Stark et al. (2009), updated to include v2 GOODS ACS photometry, and the BPZ software (Benitez et al. 2000). Details of the photometric redshift methodology is discussed in Stark et al. (2009). Using the probability distributions derived from BPZ, we compute the probability

that each object lies outside the redshift range constrained by our spectroscopic observations (typically  $z \lesssim 3.4$ ). We then place those galaxies without spectroscopic redshifts in bins of UV luminosity and compute the total contamination fraction as a function of UV luminosity. As expected, the results show that the contamination fraction increases toward lower luminosities. We find negligible contamination for bright sources ( $-22 \lesssim M_{\text{UV}} \lesssim -20$ ) with SEDs constrained by high S/N photometry. In the two faintest absolute magnitude bins considered ( $M_{\text{UV}} = -19$  and  $-18$ ), the predicted contamination increases to  $\simeq 10\%$ . This suggests that, owing to low- $z$  contamination, the true Ly $\alpha$  fractions in the two faintest bins should be  $1.11\times$  greater than derived. We consider the effects of this in our discussion of the Ly $\alpha$  fraction in §4.1.

We now examine whether the SEDs predict contamination should vary strongly with redshift. As above, we measure the contamination fraction (of objects that are not Ly $\alpha$  emitters) implied for B, V, and  $i'$ -drop samples from the photometric probability distributions. As above, we find negligible contamination at the brighter magnitudes. Combining sources with UV luminosities spanning  $-20 \lesssim M_{\text{UV}} \lesssim -18$ , we find that the contamination fraction increases from 2% for V and  $i'$ -drops to 5% for B-drops. This suggests that in this luminosity regime, the B-drop Ly $\alpha$  fraction will be underestimated by a factor of 1.05, while the V and  $i'$ -drop Ly $\alpha$  fraction will be underestimated by a factor of 1.02. Hence low- $z$  contamination will cause the positive evolution in the Ly $\alpha$  fraction with redshift to be overestimated by a factor of 1.03 in this luminosity range. As we will show in §4.2, while the redshift-dependent trends in the Ly $\alpha$  fraction are small in their amplitude, this contamination effect contributes little to the observed variation with redshift.

## 4 ANALYSIS

We now turn to the key questions posed in §1. Armed with a large sample of LBGs for which some fraction,  $x_{\text{Ly}\alpha}$ , show Ly $\alpha$  emission, we discuss what can be learned about the demographics of line emission in the star-forming population and how such trends might affect our ability to use Ly $\alpha$  as a tracer of reionization. In this analysis section, first we present the results, both in terms of the fraction of LBGs showing line emission as a function of luminosity and redshift. We then discuss the physical factors that might explain these trends prior to the use of Ly $\alpha$  emission statistics as a possible probe of reionisation.

### 4.1 The Luminosity-Dependence of Ly $\alpha$ emission at high-redshift

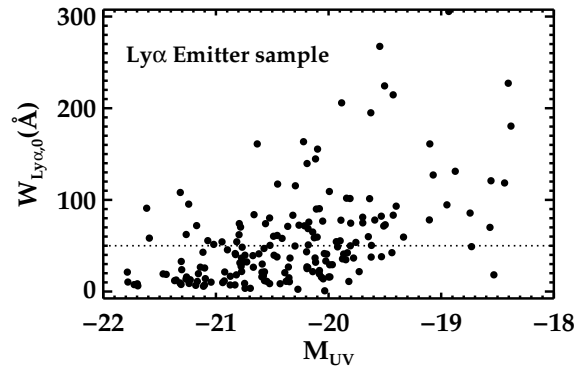
First, we discuss the relationship between Ly $\alpha$  emission and luminosity in our spectroscopic sample of Ly $\alpha$  emitters between  $3 \lesssim z \lesssim 6$ . If the Ly $\alpha$  fraction varies strongly with luminosity, as may be expected given recent claims of luminosity-dependent dust obscuration at high-redshift (Reddy & Steidel 2009; Bouwens et al. 2009b), then care must be taken to compare only galaxies of similar luminosity when searching for evolution in the Ly $\alpha$  fraction with

redshift. As our survey probes to considerably lower luminosities than past spectroscopic LBG samples at  $z \gtrsim 3$  ( $M_{UV} \simeq -18$ , Figure 6), our sample is well-suited to investigating such a relationship.

There have been a number of previous studies which examine how Ly $\alpha$  line strength varies with luminosity. Many of these studies have reported a correlation between Ly $\alpha$  equivalent width and UV luminosity. Shapley et al. (2003) binned their sample of  $z \simeq 3$  galaxies with  $W_{Ly\alpha,0} > 20 \text{ \AA}$  in three groups of apparent UV luminosity and found that the mean of the  $W_{Ly\alpha,0}$  distribution increased toward fainter UV luminosity. Others have examined Ly $\alpha$  equivalent widths as a function of UV continuum luminosity, revealing a deficit in large equivalent width Ly $\alpha$  lines in the most luminous continuum sources (Ando et al. 2006; Ouchi et al. 2008; Pentericci et al. 2009; Vanzella et al. 2009; Balestra et al. 2010). Additionally, by comparing the UV luminosity function of LBGs with that of narrowband-selected LAEs, Ouchi et al. (2008) has shown that Ly $\alpha$  emitters are likely to be more prevalent at the faint-end of the luminosity function. As we discussed earlier, these results are consistent with simple theoretical expectations in which low luminosity galaxies are less obscured by dust (due to lower metallicities) and perhaps have lower column densities (or covering fraction) of HI surrounding them (e.g. Verhamme et al. 2006, 2008; Schaerer & Verhamme 2008). Perhaps of equal or greater importance is the bulk velocity field of the HI (Shapley et al. 2003; Steidel et al. 2010), which we discuss further in §4.3.

However, others have found the evidence for a correlation between luminosity and Ly $\alpha$  equivalent width to be less convincing (e.g. Steidel et al. 2000; Nilsson et al. 2009). In particular, Nilsson et al. (2009) demonstrated that the dearth of luminous galaxies with extreme Ly $\alpha$  emission in magnitude or flux-limited surveys does not require the equivalent width distribution to be luminosity-dependent. The lack of such extreme emitters is actually expected in a magnitude or flux limited survey, as the most luminous and the most extreme emitters are both rare, causing this portion of parameter space to poorly represented unless very large volumes are covered. This is an important realisation but only considers LBGs with continuum luminosities brighter than  $M_{UV} \simeq -20$ , significantly more luminous than the feeble sources probed in our survey. Likewise, Kornei et al. (2009) found only marginal evidence for a correlation between  $W_{Ly\alpha}$  and UV continuum luminosity in a large sample of  $z \simeq 3$  LBGs, but concluded that this may result from the limited dynamic range in UV luminosity probed by their sample.

Figure 12 shows the distribution of rest-frame equivalent width,  $W_{Ly\alpha,0}$  for Ly $\alpha$  emitters in our survey as a function of rest-frame UV luminosity,  $M_{UV}$ . In considering this figure we must choose a sufficiently bright  $W_{Ly\alpha,0}$  threshold to avoid incompleteness in the faintest sources. As demonstrated in §3.3 and Figure 11, sources with  $W_{Ly\alpha,0}$  in excess of  $50 \text{ \AA}$  are detected with high completeness ( $> 90\%$ ) across our spectra, so we adopt this value as our equivalent width threshold. The data show an apparent lack of strong line emission among the most luminous dropouts, as has been found elsewhere (Ando et al. 2006; Pentericci et al. 2009; Vanzella et al. 2009), yet as demonstrated in Nilsson et al. (2009), this does not necessarily imply that Ly $\alpha$  emission is



**Figure 12.** Rest-frame Ly $\alpha$  equivalent width ( $W_{Ly\alpha,0}$ ) as a function of rest-frame absolute magnitude,  $M_{UV}$  for Ly $\alpha$  emitters in our spectroscopic sample. The sample is nearly complete at all  $M_{UV}$  for sources with  $W_{Ly\alpha,0} > 50 \text{ \AA}$  (dotted line).

less common in luminous galaxies. However, when Figure 12 is viewed in concert with the absolute magnitude histogram of our spectroscopic sample (Figure 6), it becomes clear that strong line emission must be more common in low luminosity dropouts, for the number of low luminosity galaxies ( $M_{UV} > -19.5$ ) targeted in our campaign is as low as the most luminous sources ( $M_{UV} < -21.5$ ), but the number of strong line emitters is far greater among the feeble sources. We emphasize that owing to our equivalent width threshold of  $W_{Ly\alpha,0} \simeq 50 \text{ \AA}$ , the Ly $\alpha$  emitters amongst low luminosity sources are secure and robust ( $S/N > 10$ ) detections (similar to those at the top of Figure 1); hence this result is not driven by noisy features.

In order to most clearly quantify the luminosity-dependence of Ly $\alpha$  emission, we must compute the *fraction of LBGs in our spectroscopic sample that show strong Ly $\alpha$  emission*,  $x_{Ly\alpha}$ , as a function of emerging UV luminosity. Given that the majority of our spectroscopic sample is fainter than our continuum flux sensitivity (Figure 5), it is not possible to measure redshifts for faint sources without emission. Hence if we were to compute  $x_{Ly\alpha}$  based solely on sources with confirmed redshifts (as has been done previously for brighter samples), we would artificially increase  $x_{Ly\alpha}$  toward lower luminosities. To avoid this bias, we define  $x_{Ly\alpha}$  as the number of Ly $\alpha$  emitters above some  $W_{Ly\alpha,0}$  threshold divided by the total number of dropouts placed on our slitmasks.

The error on  $x_{Ly\alpha}$  is computed as follows. We first derive the Poisson error from the number of sources considered in each luminosity or redshift bin. In addition to the Poisson error, each measurement is subject to additional error owing to uncertainty in the equivalent width measurements. We thus conduct Monte Carlo simulations, randomly varying the equivalent width of each galaxy assuming a normal distribution with mean and standard deviation corresponding to the measured  $W_{Ly\alpha,0}$  and  $\sigma_W$ . For each realization, we compute the luminosity-dependent Ly $\alpha$  fraction. Considering all the trials, we compute the standard deviation in the  $x_{Ly\alpha}$  distribution. We then combine this error term in quadrature with the random error derived above. In doing these simulations, we also consider whether equivalent

width error may artificially scatter a net flux of feeble galaxies above our equivalent width threshold, introducing the observed trend. However the simulations demonstrate that this is not the case, as the trend is readily apparent in each realisation.

In constructing the Ly $\alpha$  fraction, we must also recognize that the wavelength coverage of some spectra is such that Ly $\alpha$  would not be recovered across the full redshift range over which those dropouts might be selected. This applies mostly to FORS2 spectra of B-drops which can only detect Ly $\alpha$  for sources with  $z \gtrsim 3.9$ . Given that B-drops are expected to span the redshift range  $3.5 \lesssim z \lesssim 4.5$ , this suggests that a large number of B-drops would not be recovered in the FORS2 spectra even if they showed Ly $\alpha$  in emission. We therefore limit our study of B-drops to those with spectra that allow Ly $\alpha$  to be detected over the entire redshift range expected. This is a particular advantage of the DEIMOS component of our survey where the numerous B-drops taken with the 600 line mm $^{-1}$  grating are fully sampled.

Following this procedure, we compute the luminosity-dependence of our entire spectroscopic sample. We find that  $x_{\text{Ly}\alpha}$  is considerably larger in low luminosity galaxies (Figure 13), increasing from 10-20% for luminous sources ( $M_{\text{UV}} \simeq -21$ ) to 60-70% for feeble galaxies ( $M_{\text{UV}} \simeq -18$ – $-19$ ). A similar trend is seen if we adopt larger equivalent width thresholds. The Ly $\alpha$  fraction rises slowly with decreasing luminosity over  $-22.0 \lesssim M_{\text{UV}} \lesssim -20.5$  but then begins to increase more rapidly at lower luminosities ( $-20.5 \lesssim M_{\text{UV}} \lesssim -18.5$ ). We thus fit first order polynomials over each of these luminosity ranges, finding  $x_{\text{Ly}\alpha} = 1.09 + 0.047 M_{\text{UV}}$  at the luminous end and  $x_{\text{Ly}\alpha} = 5.46 + 0.26 M_{\text{UV}}$  for the lower luminosity sources. Given that the Ly $\alpha$  fraction increases slowly for luminous sources, it is perhaps no surprise that previous studies which were limited to this luminosity regime found only moderate evidence for luminosity dependent trends (Nilsson et al. 2009; Kornei et al. 2009); it is only by probing lower luminosity galaxies that we start to see a clear trend in the prevalence of Ly $\alpha$  with luminosity.

Intriguingly, the “break” in the luminosity-dependence of the Ly $\alpha$  fraction in Figure 13 occurs at very similar luminosities to the characteristic UV luminosity of the rest-frame UV  $4 < z < 6$  luminosity function (e.g., Bouwens et al. 2007). At luminosities greater than  $L_{\text{UV}}^*$ , the Ly $\alpha$  fraction is low and increases slowly, but below this luminosity, the Ly $\alpha$  fraction increases to much larger values. While perhaps coincidence, this may suggest that whatever process modulates the knee of the luminosity function at  $z > 4$  may play a role in the escape of Ly $\alpha$  photons.

In order to put these results in context, it is interesting to estimate the escape fraction of Ly $\alpha$  photons that is implied by these large equivalent widths. In particular, we are interested in the Ly $\alpha$  escape fraction that is implied by the  $W_{\text{Ly}\alpha,0} \simeq 50 \text{ \AA}$  threshold we have adopted. Assuming a Salpeter IMF with  $M_{\text{upper}}=120 M_{\odot}$ , case B recombination, constant star formation, and metallicity ranging between  $Z=1/20 Z_{\odot}$  and  $Z_{\odot}$ , Ly $\alpha$  equivalent widths can be as high as  $\simeq 200 - 300 \text{ \AA}$  in the first few Myr of the star formation episode, asymptoting to  $\simeq 100 \text{ \AA}$  after 10 Myr (Malhotra & Rhoads 2002; Schaerer 2003). Hence our equivalent width threshold corresponds to a Ly $\alpha$  escape fraction of 15-50%. Of course, this assumes that all ionising photons

are absorbed; if there is significant Lyman continuum leakage, then the predicted equivalent widths would decrease, increasing the inferred Ly $\alpha$  escape fraction. Alternatively, if dust is confined to cold neutral clouds, then the maximum Ly $\alpha$  equivalent widths may be larger than quoted above (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2008), decreasing the implied Ly $\alpha$  escape fraction.

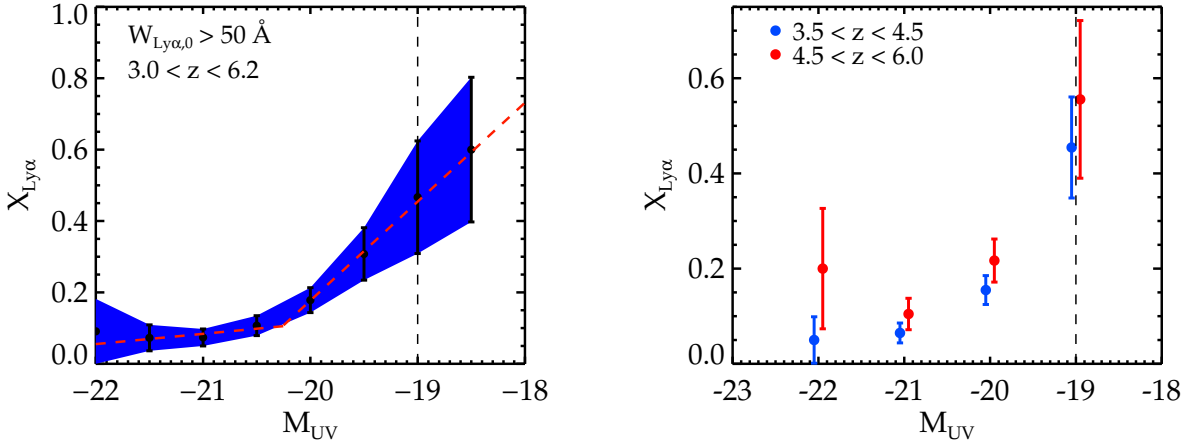
These results provide clear evidence that Ly $\alpha$  emission becomes continuously more prevalent among lower luminosity star forming galaxies. Indeed, it appears that the *majority* of feeble ( $M_{\text{UV}} < -19$ ) sources are strong Ly $\alpha$  emitters. These results appear to indicate that the escape fraction of Ly $\alpha$  photons (relative to that of far-UV continuum photons) is strongly luminosity-dependent and at very low continuum luminosities may commonly exceed the 5% robustly derived (at  $z \simeq 2$ ) via Ly $\alpha$  and H $\alpha$  surveys (Hayes et al. 2010). In the following section, we examine whether similar trends are seen with redshift, while in §4.3 we examine the physical mechanism that are likely to be governing the escape fraction of Ly $\alpha$  photons at  $z \gtrsim 3$ .

#### 4.2 Variation in the Ly $\alpha$ fraction in the redshift range $3 \lesssim z \lesssim 6$

We now examine the redshift evolution of the prevalence of Ly $\alpha$  emitters in the Lyman break galaxy population over  $3 < z < 6$ . Since the IGM appears to be highly ionised over this redshift range, this measurement provides the opportunity to understand the extent to which factors other than IGM attenuation affect the Ly $\alpha$  fraction. By calibrating these effects over this redshift interval, we can more accurately detect the signal of reionisation on the Ly $\alpha$  fraction.

We consider luminosity-dependent samples in two separate redshift bins,  $3.0 < z < 4.5$  and  $4.5 < z < 6.0$  (Figure 13). Sources without spectroscopic redshifts are placed into one bin or the other based on their photometric redshift (see Stark et al. 2009 for discussion of photometric redshifts). In each UV luminosity bin, the fraction  $x_{\text{Ly}\alpha}$  increases with redshift. The two bins with the lowest error and incompleteness ( $M_{\text{UV}} \simeq -21$  and  $-20$ ) show increases of 60% and 40%, respectively. Our equivalent width threshold and redshift binning ensures that this result is not biased by redshift-dependent incompleteness. To determine the differential growth, we compute the average change in Ly $\alpha$  fraction,  $\Delta x_{\text{Ly}\alpha}$ , across all luminosity bins (weighted by the inverse variance of each bin) and compute  $\Delta z$  using the median redshift in each of the two bins. With this approach, we find that the Ly $\alpha$  fraction increases with redshift following  $dx_{\text{Ly}\alpha}/dz \simeq 0.05$ . As we mentioned in §3.4, low- $z$  contamination appears to decrease very slightly with redshift. However, we find that this effect introduces such small changes in the Ly $\alpha$  fractions ( $\lesssim 1\%$ ) in each redshift bin, such that the weighted Ly $\alpha$  fraction redshift evolution remains as quoted above. Hence Ly $\alpha$  fractions grow by nearly  $\Delta x_{\text{Ly}\alpha} \simeq 0.1$  at fixed  $M_{\text{UV}}$  between  $z \simeq 4$  and  $z \simeq 6$ .

We emphasize that this trend is not driven by biases associated with LBG selection. It is well-established that the presence of strong Ly $\alpha$  can affect the broadband colours used for dropout selection (Stanway et al. 2007, 2008). Line emission can either boost the dropout color (if the redshift is at the high end of the distribution with Ly $\alpha$  in the red filter) or it can dilute the color (if the redshift is at



**Figure 13.** (Left:) Fraction of spectroscopic dropout sample showing strong Ly $\alpha$  emission ( $W_{\text{Ly}\alpha,0} > 50 \text{ \AA}$ ) as a function of UV luminosity. The dashed lines corresponds to first order polynomial fits to the Ly $\alpha$  fractions in the range  $-22.0 \lesssim M_{\text{UV}} \lesssim -20.5$  and  $-20.0 \lesssim M_{\text{UV}} \lesssim -18.5$ . (Right:) Fraction of spectroscopic dropout sample showing strong Ly $\alpha$  emission ( $W_{\text{Ly}\alpha} > 50 \text{ \AA}$ ) as a function of UV luminosity for samples with  $3.5 < z < 4.5$  (blue circles) and  $4.5 < z < 6.0$  (red circles). Vertical lines correspond to  $\simeq 90\%$  completeness limits for B and V-drop samples. For the  $i'$ -drops, the completeness limits are  $\simeq 0.7$  mags brighter. Any incompleteness would serve to increase the Ly $\alpha$  fractions further.

the low end with Ly $\alpha$  in the bluer filter). In principle, this could lead to Ly $\alpha$  being preferentially recovered at higher redshifts. But we minimize these biases by simultaneously targeting the B, V, and  $i'$ -dropout population. For example, sources with very strong Ly $\alpha$  emission at  $5.5 < z < 5.7$  (such that the line falls in the  $i'_{775}$ -band) may be scattered out of the  $i'$ -drop selection but would instead appear in V-drop selections. Thus, in this case, by conducting spectroscopy of V-drops, we can account for this diffusion of Ly $\alpha$  sources. Similarly, our B-drop sample will contain the small number of sources at  $4.5 < z < 4.8$  with very high strong Ly $\alpha$  contaminating the  $V_{606}$ -band filter (which would otherwise have little flux). While we don't target U-drops, Ly $\alpha$  emission from galaxies at  $3.5 < z < 3.8$  does not contaminate the  $B_{435}$ -band filter, so our B-drop sample should not have redshift-dependent biases.

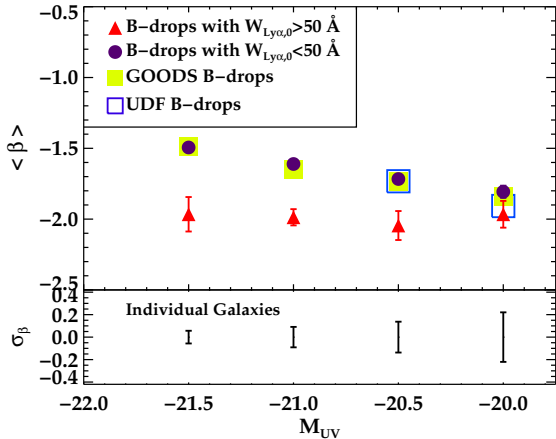
The redshift dependence of  $x_{\text{Ly}\alpha}$  is affected not only by evolution in the internal properties of galaxies but also by the increase in the density of the IGM with redshift. At  $z \simeq 6$ , the IGM provides a significantly greater optical depth to Ly $\alpha$  photons than that at  $z \simeq 4$ , resulting in a second order affect on the Ly $\alpha$  fraction. In the absence of IGM density evolution, we would thus expect the redshift evolution of the Ly $\alpha$  fraction to be slightly greater than derived above. We can attempt to estimate the variation in  $x_{\text{Ly}\alpha}$  that is intrinsic to *galaxy evolution* (e.g. dust, ISM kinematics) by subtracting the differential evolution expected from changes in IGM density. Deconvolving the effects of the IGM on Ly $\alpha$  radiative transfer requires careful modeling of the local density, velocity, and ionisation field (e.g. Santos 2004; Dijkstra et al. 2007a,b; Zheng et al. 2009). We delay such a treatment to subsequent works, and instead we follow a very simple approach adopted in Ouchi et al. (2008) which yields a very rough estimate on the intrinsic redshift evolution of the Ly $\alpha$  fraction. We compute the percentage of photons absorbed by the IGM assuming that the blue side

of the Ly $\alpha$  line is attenuated by  $\exp[\tau_{\alpha}(z)]$ , where  $\tau_{\alpha}(z)$  is the optical depth for Ly $\alpha$  photons as computed in Meiksin (2006). With this approach, we find that the IGM absorbs 28, 42, and 49% of the Ly $\alpha$  line flux at  $z \simeq 4, 5$ , and 6. In a more sophisticated and realistic treatment, the density and ionising background surrounding Ly $\alpha$  emitters is likely to be greater than the mean, and infalling gas would also erase a fraction of the Ly $\alpha$  line redward of rest-frame 1216  $\text{\AA}$ ; the combination of these effects can cause the redshift evolution in the transmission of Ly $\alpha$  photons through a reionised IGM to be considerably different than implied by our model above (e.g., Santos 2004; Dijkstra et al. 2007b). We will model this effect in greater detail in the future. For the sake of clarity, here we define the intrinsic  $W_{\text{Ly}\alpha,0,\text{int}}$  as the rest-frame equivalent width that would have been observed if not for IGM attenuation, where the IGM absorption is taken to follow the numbers derived above. Adopting a fixed intrinsic  $W_{\text{Ly}\alpha,0,\text{int}}$ , we derive Ly $\alpha$  fractions as above and find that the differential redshift evolution in  $x_{\text{Ly}\alpha}$  increases to  $dx_{\text{Ly}\alpha}/dz \simeq 0.12$ . In the next section, we attempt to understand the factors likely to be creating this redshift trend and the luminosity trend presented in the previous section.

### 4.3 The factors governing the Ly $\alpha$ escape fraction

Earlier we demonstrated that prevalence of strong Ly $\alpha$  emission increases toward lower luminosities and higher redshifts. Here we discuss the factors that are likely governing the observed trends prior to exploring the use of higher redshift galaxies and their line emission as a probe of cosmic reionisation. In §4.3.1, we examine whether trends in dust obscuration could potentially drive the observed Ly $\alpha$  fraction relations. In §4.3.2 and §4.3.3, we discuss how the geometric distribution and kinematics of the surrounding ISM may impact the Ly $\alpha$  fraction trends we observe and discuss fu-





**Figure 14.** Average UV slopes of B-drops with and without strong Ly $\alpha$  emission. Average UV slopes of B-drops (grouped in bins of  $M_{UV}$ ) from the spectroscopic sample with strong Ly $\alpha$  emission ( $W_{Ly\alpha,0} > 50$  Å) are denoted by red triangles, while the average UV slopes rest of the B-drop sample is denoted by purple circles. For reference, we overplot the average UV slope as a function of  $M_{UV}$  for the entire photometric sample of B-drops in GOODS-N and GOODS-S from Stark et al. (2009) as filled yellow squares. The average UV slope from B-drops in the Hubble UDF is shown as open blue squares. Typical uncertainties in the UV slopes of individual galaxies are shown as error bars on the bottom of the plot; uncertainties in the mean take both this error and the number of sources in each bin into account.

ture spectroscopic work in progress to provide further insight into the ISM of feeble high- $z$  galaxies. Finally in §4.3.4 and §4.3.5, we close our discussion with a variety of factors possibly affecting Ly $\alpha$  that are more difficult to directly constrain observationally.

#### 4.3.1 Impact of dust extinction

Previous observations have demonstrated that, among luminous LBGs, those objects showing Ly $\alpha$  in emission tend to display bluer UV continuum slopes than those with Ly $\alpha$  absorption (Shapley et al. 2001, 2003; Vanzella et al. 2009; Pentericci et al. 2009; Kornei et al. 2009). While the presence of dust may enhance Ly $\alpha$  relative to the continuum (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2008), the results in Figure 14 suggest that most often, the presence of significant quantities of dust generally leads to increased absorption of Ly $\alpha$  photons relative to the continuum.

Here, we examine whether similar trends are seen at lower luminosities. In order not to bias the UV colors, we determine the slopes using filters that are not contaminated with Ly $\alpha$  emission or IGM absorption. Obtaining accurate UV slopes requires very accurate color measurements, thus we choose to focus on the B-drops, as the UV colors can be determined entirely from deep  $i'$  and  $z$ -band imaging with ACS. We translate the UV colors into UV slopes using the relation presented in Bouwens et al. (2009b):  $\beta = 5.30(i'_{775} - z_{850}) - 2.04$ . We have verified that this relation holds for a variety of star formation histories and age combinations that are appropriate for the  $z \simeq 4 - 6$  population.

Given the relationship between UV color and  $\beta$ , it is

important to note that even a small photometric colour error translates into substantial uncertainty in the derived UV slope. We thus estimate the luminosity limit at which the GOODS data become unreliable for estimating UV slopes by comparing the average UV slopes of B-drops in GOODS with UV slope measurements from higher S/N data in the UDF, using the photometric catalogs of Coe et al. (2006) for our UDF sample. These results indicate that UV slopes measured from the GOODS dataset differ significantly from those determined from the high S/N UDF sample for B-drops with luminosities fainter than  $M_{UV} \simeq -20.5$ . Therefore, we cannot derive robust UV slopes for sources in our GOODS spectroscopic sample that are fainter than this limit.

Concentrating on the brighter subset of objects, we examine the UV slopes of our B-drop spectroscopic sample as a function of UV luminosity (Figure 14). The data show that galaxies with strong Ly $\alpha$  in emission ( $W_{Ly\alpha,0} > 50$  Å) are bluer than those systems without strong Ly $\alpha$  emission, and are generally fit with  $\beta = -2.0$  across the entire luminosity range covered. Following Meurer et al. (1999), this value is consistent with very little dust obscuration ( $A_{1600} \simeq 0.5$ ), assuming a Calzetti extinction curve and normal stellar populations. The UV slopes of the overall population of B-drops are significantly redder than the Ly $\alpha$  emitters, but when viewed as a function of luminosity, they grow steadily bluer toward low luminosities, ranging from  $\beta \simeq -1.5$  (at  $M_{UV} \simeq -21.5$ ) to  $\beta \simeq -1.7$  (at  $M_{UV} \simeq -20.5$ ). The correlation between UV slope and emerging UV luminosity at these redshifts was first demonstrated in a large photometric sample in Bouwens et al. (2009b); here we confirm this trend with a spectroscopic sample of dropouts. As argued in Bouwens et al. (2009b), the trend most likely arises as a result of lower luminosity galaxies having less dust obscuration. Given that strong Ly $\alpha$  emitters tend to arise in galaxies with little dust extinction, it is perhaps no surprise that we see a larger Ly $\alpha$  fraction in low luminosity galaxies. Similar reasoning can also explain the observed redshift-dependence of the Ly $\alpha$  fraction, as UV slopes are found to grow steadily bluer with redshift over  $3 \lesssim z \lesssim 6$  (Bouwens et al. 2009b).

If we attribute the luminosity-dependence of the Ly $\alpha$  fraction to the variation in dust obscuration, we can derive a relationship between mean UV slope and Ly $\alpha$  fraction. From Figure 14, we find that  $d\beta/dM_{UV} \simeq -0.23$  over  $-21.5 < M_{UV} < -20.0$ . This is similar, but slightly steeper, than the value derived in Bouwens et al. (2009b). Over this same luminosity range, we derive  $dx_{Ly\alpha}/dM_{UV} = 0.29$ . Assuming that dust extinction drives the evolution in the Ly $\alpha$  fraction, we derive  $dx_{Ly\alpha}/d\beta = -1.2$ . While this result was derived from the luminosity-dependence of  $x_{Ly\alpha}$ , it should also apply to the redshift evolution if dust obscuration were to dominate the redshift-dependent trends. Measurements of similarly luminous  $z \simeq 6$  LBGs (Bouwens et al. 2009b) suggest that the average UV slopes grow bluer by  $\Delta\beta \simeq -0.6$  from  $z \simeq 4$  to  $z \simeq 6$ . If dust evolution dominates the redshift-dependence of the Ly $\alpha$  fraction and the evolution in UV slopes, the above relationship suggests that  $x_{Ly\alpha}$  should increase by  $\Delta x_{Ly\alpha} = 0.84$ . The fact that the actual redshift evolution is significantly less rapid ( $\Delta x_{Ly\alpha} = 0.24$  after roughly accounting for IGM absorption) can be explained by several factors. For example, it is likely that the luminosity dependence of  $x_{Ly\alpha}$  is driven by more than just dust

obscuration (see the following sections for a discussion). Additionally as UV slopes grow bluer than  $\beta = -2.0$ , the variation in the UV slope is possibly driven by factors other than dust obscuration (e.g., Stanway et al. 2005; Bouwens et al. 2010a). Secondly, given that  $x_{Ly\alpha}$  cannot be larger than 1.0, the differential growth must slow down as  $x_{Ly\alpha}$  increases; hence any extrapolation of the  $x_{Ly\alpha}$  relations below our completeness limits is highly uncertain. Finally, as emphasized in §4.2, our simple treatment of IGM absorption may incorrectly estimate the evolution in the  $Ly\alpha$  fraction that is intrinsic to galaxy processes.

In summary, these results indicate that the variation in dust extinction with luminosity and redshift likely plays an important role in governing the observed evolution and luminosity-dependence in the  $Ly\alpha$  fractions. But, not surprisingly, it seems likely that additional factors play a role in governing  $x_{Ly\alpha}$  as well. We discuss these in more detail below.

#### 4.3.2 The hydrogen covering fraction

After  $Ly\alpha$  photons escape the H II regions where they were created, they must diffuse through neutral gas and dust at larger radii. This could include gas that is participating in outflows surrounding the galaxy in addition to gas that is being accreted onto the galaxies. Rest-UV spectra of high-redshift star-forming galaxies reveal low-ionisation absorption lines that are generally blue-shifted by  $\Delta v \simeq -200$  km s<sup>-1</sup> (Shapley et al. 2003; Steidel et al. 2010) relative to the centre of rest, indicating that outflowing neutral gas is nearly always present, while accreting gas appears less prevalent. The geometrical distribution and kinematics of this outflowing material plays a crucial role in governing the escape of  $Ly\alpha$  photons. This is clearly evidenced by the fact that  $Ly\alpha$  photons are typically observed to be redshifted by  $\simeq 400 - 500$  km s<sup>-1</sup> with respect to the centre of rest (Steidel et al. 2010). This result implies that the majority of  $Ly\alpha$  photons to escape through the absorbing material along the line of sight are those that achieve a sufficient (redshifted) velocity such that they can travel through the intervening material without resonantly scattering. This is most easily accomplished in a model in which the  $Ly\alpha$  photons that are observed are those that have been “backscattered” off of the outflowing material on the far side of the galaxy (e.g., Shapley et al. 2003; Steidel et al. 2010). Hence, it is likely that the increased prevalence of  $Ly\alpha$  emitters among low luminosity galaxies tells us something about the distribution and/or kinematics of the ISM of feeble sources. In this section, we discuss the relationship of the ISM distribution, dust obscuration, and  $Ly\alpha$  emission in luminous LBGs as found in previous work, and then consider whether a similar picture is likely to hold for low luminosity galaxies; in the following section, we focus on the kinematics of the ISM.

Even for luminous sources, observational constraints on the distribution of the blueshifted neutral absorbing gas in the immediate vicinity of high redshift galaxies are limited. The spectroscopic study of  $z \simeq 3$  LBGs conducted in Shapley et al. (2003) revealed a strong correlation between the equivalent width of low-ionisation interstellar absorption lines ( $W_{LIS}$ ) and that of  $Ly\alpha$ , in the sense that the strongest  $Ly\alpha$  emitters tend to have the least absorption by the low-ionisation interstellar medium. As the absorption lines are

highly saturated, Shapley et al. (2003) note that the trend in  $W_{LIS}$  is due either to variations in the velocity width or the covering fraction of absorbing gas, with the latter argued to be the dominant factor, such that sources showing strong  $Ly\alpha$  emission, on average, have the patchiest distribution of absorbing gas covering the continuum source (at least along the line of sight). Galaxies also show a strong correlation between  $W_{LIS}$  and E(B-V), which Shapley et al. (2003) argue implies a significant fraction of the dust which reddens the stellar continuum (and absorbs  $Ly\alpha$  photons) is located *within* the outflowing neutral gas. As noted in Steidel et al. (2010), from a theoretical standpoint, the exact effect of a non-uniform covering fraction on the observed  $Ly\alpha$  flux is not obvious. But regardless, these observations thus suggest a scenario in which strong  $Ly\alpha$  emission is generally coupled with low dust extinction and a low hydrogen covering fraction, a picture supported by recent observations of strongly-lensed LBGs at  $z \simeq 3$  (Quider et al. 2009, 2010) for which direct measures of the covering fractions of various ions are available.

If similar trends are present in low luminosity galaxies, then the fact that  $Ly\alpha$  is much more common in feeble galaxies may imply that these sources typically have lower covering fractions of absorbing gas than more luminous LBGs. Addressing whether this is indeed the case requires deep spectroscopy of UV-faint systems, and thus is perhaps only feasible via studies of gravitationally-lensed galaxies. Some progress can be made with current field samples however. In particular, we can determine whether the coupling between strong  $Ly\alpha$  emitters and weak ISM absorption is also present for feeble galaxies by creating composite spectra of  $Ly\alpha$  emitters binned by  $M_{UV}$ . We will present the results of this analysis in a subsequent paper (Stark et al. 2010, in preparation). Some indication that the correlation is in place at low intrinsic luminosities is already apparent from the  $i'$ -drop composite spectra presented in Vanzella et al. (2009). As all the  $i'$ -drops in their sample are UV faint ( $< M_{UV} \gtrsim -20$ ), this spectrum provides insight into the properties of feeble sources. Owing to the faintness of the  $i'$ -drops, the composite is dominated by strong  $Ly\alpha$  emitters and shows very weak interstellar absorption lines. Higher S/N spectra are required to ensure that the absorption lines are saturated and to quantify the absorption line equivalent widths.

Finally, while admittedly speculative, we note briefly that if a low hydrogen covering fraction is more common for low luminosity galaxies, it may also enable Lyman continuum photons to more easily escape from feeble systems. Naively, this statement seems contradictory since the presence of  $Ly\alpha$  photons stems from the absorption of ionising photons. However high-redshift galaxies are clearly not perfect H II regions. In practice, a significant fraction of ionising photons are absorbed in the ionised regions surrounding the massive stars, leading to the production of  $Ly\alpha$  photons. Both  $Ly\alpha$  photons as well as any escaping ionising photons will then approach the surrounding neutral ISM, much of which is likely moving at great speeds with respect to the stars. Clearly, those systems with significant holes in their surrounding distribution of hydrogen will leak a larger fraction of ionising radiation. Indeed, the combination of strong  $Ly\alpha$  and significant ionising photon escape fractions are seen in observations at  $z \simeq 2$  (Shapley et al. 2006). Intriguingly,



recent results reveal a possible trend toward greater Lyman continuum leakage in sources with low UV continuum luminosities (Steidel et al. 2010, in preparation). While much work is still required to verify the luminosity-dependence in the hydrogen covering fraction and the Lyman continuum escape fraction, these results strongly motivate detailed study of the physical properties of low luminosity galaxies.

#### 4.3.3 Kinematics of ISM

As we discussed above, Ly $\alpha$  is affected not only by the geometry and column density of the dust and hydrogen around it but also by the velocity distribution of the surrounding neutral HI. Recently, Steidel et al. (2010) has compared the kinematics of the absorbing gas (extracted from the properties of rest-UV absorption lines) and the properties of Ly $\alpha$  as a function of total baryon mass for a sample of  $z \simeq 2$  UV continuum selected galaxies. These results reveal that the low mass subset shows significantly stronger Ly $\alpha$  emission, as we would expect from Figure 13, on the assumption that the feeble sources that we have studied spectroscopically are generally lower mass systems. Steidel et al. (2010) demonstrate that the absorbing medium is significantly different for these two mass subsets, with the more massive galaxies more often having a significant component of interstellar absorption at velocities close to the systemic redshift (and often extending to positive velocities). These high mass systems not only have weaker Ly $\alpha$  emission but the redshifted velocity of Ly $\alpha$  is greater than in low mass galaxies. The nature of this excess absorption component at zero velocity for massive galaxies is unclear; as discussed in detail in Steidel et al. (2010) it could possibly be outflowing material which has stalled due perhaps to the larger gravitational potential, or alternatively infalling gas.

Regardless, it is clear that there are significant mass-dependent variations in the kinematics of the absorbing gas, particularly at  $v = 0$ , such that lower mass galaxies transmit a larger fraction of their Ly $\alpha$  photons to earth. These trends, together with those seen in dust obscuration and perhaps hydrogen covering fraction, may play a large role in governing the luminosity-dependence of the Ly $\alpha$  fraction seen in Figure 13. Future spectroscopic work of feeble galaxies which are magnified via gravitational lensing can help confirm these mass-dependent trends in the ISM kinematics.

#### 4.3.4 Additional Factors Governing the Ly $\alpha$ fraction

We conclude by mentioning several additional factors which may contribute to the observed Ly $\alpha$  fraction trends. Firstly, the Ly $\alpha$  equivalent width is highest in the earliest stages of star formation (Charlot & Fall 1993; Leitherer et al. 1999), when the contribution from massive, young stars is at its greatest. Studies of UV faint narrowband LAEs have generally shown that these sources have younger ages and higher specific star formation rates than more luminous LBGs (e.g. Pirzkal et al. 2007; Ono et al. 2010). However, a recent study of spectroscopically-confirmed LBGs has demonstrated that those sources with strong Ly $\alpha$  emission tend to be older than those without Ly $\alpha$  emission at similar UV luminosities (Shapley et al. 2001; Kornei et al. 2009), leading the authors to suggest a physical picture whereby Ly $\alpha$

emission escapes more easily once large-scale outflows have had time to reduce the dust covering fraction sufficiently. The sample presented in this paper allows us to extend the work of Kornei et al. (2009) to lower continuum luminosities, which we plan to present a future study (Stark et al. 2010, in preparation), taking care to account for the possible contribution of nebular emission lines to the mid-IR flux (e.g. Schaerer & de Barros 2009).

Additionally, Ly $\alpha$  equivalent width becomes larger at low metallicities owing to the increased ionising flux and harder UV spectra (e.g., Schaerer 2003). Thus if low luminosity galaxies have much lower metallicities than luminous systems, then we may expect to see an increased fraction of strong line emitters among UV faint systems. Only via future direct measurements of the metallicity of low luminosity galaxies at these redshifts will we be able to predict the magnitude of this effect on the luminosity dependence of the Ly $\alpha$  fraction.

Finally, it is, in principle, conceivable that the trends could be driven by variation in the stellar IMF with luminosity and redshift. As has been demonstrated in previous studies (Schaerer 2003), top-heavy IMFs can boost the equivalent widths of Ly $\alpha$  relative to that expected for normal stellar populations. While several studies have argued that the IMF may vary with redshift (e.g. Davé 2008), there is little direct evidence of such a variation.

#### 4.4 Comparison with narrowband Ly $\alpha$ emitter studies

Finally, we compare our results to those determined from studies of narrowband-selected Ly $\alpha$  emitters (LAEs) in the same redshift range (e.g. Shimasaku et al. 2006; Kashikawa et al. 2006; Ouchi et al. 2008). We first contrast the two samples and examine whether the large fraction of strong Ly $\alpha$  emission seen among our UV faint dropouts is consistent with the independently-determined luminosity functions of LAEs. Then we consider whether we can use the Ly $\alpha$  trends discovered in our UV continuum samples to explain the lack of redshift evolution in the luminosity functions of the LAE population, which contrasts markedly with the strong evolution seen in the LBG samples.

It is commonly asserted that narrowband LAE samples are fainter than UV continuum LBG samples. While this is true if one compares the LAE samples to the well-studied spectroscopic  $z \simeq 3$  population (e.g. Shapley et al. 2001, 2003), current photometric LBG samples extend to much fainter UV luminosities (e.g.,  $M_{UV} \simeq -16$  at  $z \simeq 4$  in the Ultra Deep Field), and as we have discussed above, our spectroscopic observations take advantage of these faint samples, extending to  $M_{UV} \simeq -18$  (Figure 2). Many LAEs identified in typical ground-based surveys are below the UV continuum magnitude limits and require stacking to determine the typical continuum luminosity. In a recent analysis of a large sample of  $z = 3.1$  LAEs, Ono et al. (2010) have shown that the stacked continuum magnitude is  $i' \simeq 27$ , corresponding to  $M_{UV} \simeq -18.6$ , comparable to the UV continuum luminosity of the faintest galaxies in our spectroscopic sample. Thus by probing down the LBG luminosity function in our DEIMOS survey, we are able to directly compare the Ly $\alpha$  trends discovered in both populations.

Consider the percentage of LBGs at a given redshift

that show strong Ly $\alpha$  emission. Assuming that LBGs form the parent population of Ly $\alpha$  emitters, we can compute the expected number density of strong Ly $\alpha$  emitters as a function of  $M_{UV}$ . Our spectroscopic data suggests that 10% of B-drops with  $M_{UV} \simeq -21$  show Ly $\alpha$  emission with  $W_{Ly\alpha,0} > 50$  Å. Based on the number density of LBGs in this luminosity range, these data predict that the density of strong line emitters with  $M_{UV} \simeq -21$  should be  $\simeq 1.8 \times 10^{-5}$  Mpc $^{-3}$  mag $^{-1}$ . This value is very similar to the abundance of LAEs in this luminosity range from the UV luminosity functions of narrowband Ly $\alpha$  emitters at  $z \simeq 4$  ( $1.2 \times 10^{-5}$  Mpc $^{-3}$ ) (Ouchi et al. 2008). Clearly this calculation is very uncertain owing to the different selection and equivalent width limits, and is meant as a zeroth order comparison. We note that of the 26  $z = 3.7$  LAEs in Ouchi et al. (2009), 23 have rest-frame equivalent widths greater than our threshold of  $\simeq 50$  Å, so the LAE sample isn't probing significantly further down the equivalent width distribution than our LBG sample. At fainter continuum luminosities ( $M_{UV} > -20$ ), the agreement begins to break down, as our measured Ly $\alpha$  fractions predict a larger abundance of LAEs than inferred from the Ouchi et al. (2008) UV luminosity functions. This is not surprising given that the Ouchi et al. (2008) is only computed over  $-21.7 < M_{UV} < -19.7$ , (where the data are sufficiently complete), requiring  $M_{UV}^*$  and  $\alpha$  to be fixed.

Finally we consider whether the observed evolution of the Ly $\alpha$  population over  $3 \lesssim z \lesssim 6$  is qualitatively consistent with the trends suggested by the luminosity and redshift-dependence of the Ly $\alpha$  fraction. The rapid increase in the Ly $\alpha$  fraction toward lower luminosities suggests that deep narrowband Ly $\alpha$  samples will generally be dominated by UV faint galaxies. Since the redshift evolution of the number density of UV faint LBGs is much less rapid than that of luminous LBGs, we expect the number density of Ly $\alpha$  emitters (which should be weighted more toward UV faint sources) to decrease less rapidly than LBG samples. This trend is enhanced by the increase in the prevalence of Ly $\alpha$  emission in LBGs over this redshift interval. Hence given the luminosity and redshift-dependent trends in the Ly $\alpha$  fraction, it is not necessarily surprising that Ouchi et al. (2008) reveal that the observed Ly $\alpha$  luminosity function does not evolve significantly with redshift over  $3.1 < z < 5.7$ .

## 5 IMPLICATIONS FOR REIONISATION

In the previous section, we showed that strong Ly $\alpha$ -emitters become more common between  $z \simeq 3$  and  $z \simeq 6$ . We argued that this trend is likely driven in part by a decrease in dust extinction and the covering fraction of hydrogen surrounding the H II regions where Ly $\alpha$  photons are originally produced. The first estimates of UV slopes at  $z \gtrsim 6$  imply that the dust obscuration continues to decline to  $z \simeq 7-8$ . Given these trends, the expected signal of reionisation (decreasing the prevalence of Ly $\alpha$  emitters) should be readily apparent in deep spectroscopy of newly discovered  $z_{850}$ -band and  $Y_{105}$ -band dropouts (e.g. McLure et al. 2010; Oesch et al. 2010; Bunker et al. 2010; Bouwens et al. 2010a; Wilkins et al. 2010a,b).

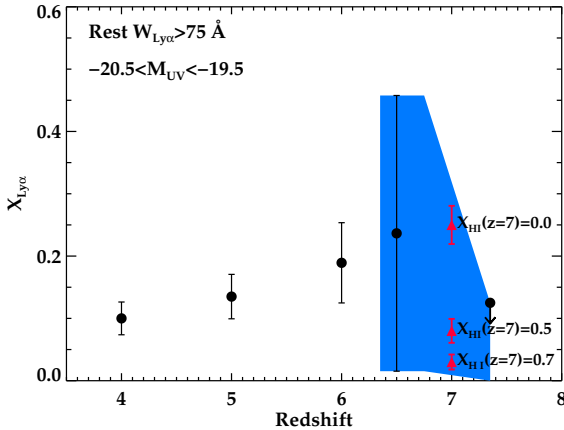
Given the increase we find in the Ly $\alpha$ -emitting fraction over  $3 \lesssim z \lesssim 6$  (Figure 13) it is now interesting to examine whether there is any decline seen beyond  $z \simeq 6$

such as might arise from an increasing neutral fraction in the IGM. Although our first set of  $z$ -drop observations were conducted in poor conditions, we can still provide preliminary constraints on  $x_{Ly\alpha}$  if we adopt a sufficiently bright equivalent width and magnitude limit. The flux limits from the October 2009 run indicate that detection requires an equivalent width of at least 75 Å (rest-frame) for sources in the luminosity bin  $-20.5 \lesssim M_{UV} \lesssim -19.5$  (§2.1). The Ly $\alpha$  equivalent widths of sources fainter than this limit (all but two of the  $z$ -drops in the UDF) are not usefully constrained. Also, owing to the increased noise stemming from poor atmospheric conditions it is not possible to detect Ly $\alpha$  with typical equivalent widths in any of the sources studied at redshifts beyond  $z \simeq 6.65$ . Over the redshift range in which we are sensitive to Ly $\alpha$  emission, completeness simulations indicate that recovery rate of lines with  $W_{Ly\alpha,0} > 75$  Å is  $\simeq 50\%$ . The photometric redshifts derived from the broadband SEDs indicate that five of the eight  $z$ -drops are likely to lie at redshifts above  $z \simeq 6.65$ . If this is true, these objects would escape detection in our DEIMOS spectra. We take this possibility into account in our discussion of the Ly $\alpha$  fractions below.

Figure 15 shows the overall evolution in the Ly $\alpha$  fraction with redshift within this restricted luminosity range. The fraction of LBGs with Ly $\alpha$  emission above our chosen threshold grows steadily over  $4 \lesssim z \lesssim 6$ , reaching nearly 20% at  $z \simeq 6$ . Based on our discussion in the previous section, we argue that this net change likely arises from a combination of the redshift evolution in the dust and hydrogen covering fractions (which increases the Ly $\alpha$  fraction toward higher redshift) and the IGM density (which decreases the Ly $\alpha$  fraction toward higher redshift).

If the line shown in Figure 8 is Ly $\alpha$ , and if all  $z$ -drops in our restricted luminosity range ( $-20.5 < M_{UV} < -19.5$ ) lie at  $z \lesssim 6.65$  (as is necessary for detection with DEIMOS in the October dataset), then our measurements would indicate that the fraction from the October run with  $W_{Ly\alpha} > 75$  Å (corrected for incompleteness) is marginally greater than that measured at  $z \simeq 6$ , consistent with the slow increase over  $4 < z < 6$ . However, given the very large errors in the Ly $\alpha$  fraction, the  $z \simeq 6.5$  measurements are also fully consistent with a significant decline over  $6.0 < z < 6.5$ . However we point out that the measured Ly $\alpha$  fraction may actually be larger than we estimate here, for if five of the  $z$ -drops are indeed at  $z > 6.65$ , as suggested by their photometric redshifts, then the Ly $\alpha$  fraction at  $z \simeq 6.5$  would be  $\simeq 2.6\times$  larger than the datapoint in Figure 15 indicates. Clearly additional spectroscopy in improved atmospheric conditions is required for robust statements.

Beyond  $z \simeq 6.6$ , existing datasets imply that the Ly $\alpha$  fraction may begin to decline. In contrast to the abundant samples of robust LBGs now in place at  $z \simeq 7$  and beyond (e.g. McLure et al. 2010; Bunker et al. 2010; Oesch et al. 2010; Bouwens et al. 2010a), searches for Ly $\alpha$  emitters at  $z > 7$  with narrowband filters have yet to reveal a large population of line emitters. While candidates have been identified (e.g. Stark et al. 2007b; Hibon et al. 2009), confirmation has proven challenging. Indeed, the highest redshift Ly $\alpha$  emitter with robust spectroscopic verification lies at  $z = 6.96$  (Iye et al. 2006). Updated data from this survey (Ota et al. 2008) suggest that the number density of Ly $\alpha$  emitters at  $z = 7.0$  is only 17% of that at  $z = 6.6$ .



**Figure 15.** Fraction of spectroscopic dropout sample with  $-20.5 < M_{UV} < -19.5$  showing strong Ly $\alpha$  emission ( $W_{Ly\alpha} > 75 \text{ \AA}$ ) over  $4 < z < 7$ . We estimate the Ly $\alpha$  fraction at  $z \simeq 6.5$  from a recent DEIMOS run targeting WFC3 z-drops. Owing to poor atmospheric conditions on this run, statistics are insufficient to robustly constrain the evolution in  $x_{Ly\alpha}$ . However in contrast, the implied Ly $\alpha$  fraction from the lack of Ly $\alpha$  detection in a sample of 8 lensed z-drops studied with near-IR spectroscopy in Richard et al. (2008) and Kneib et al. (2004) is shown by the upper limit at  $z = 7.3$ . If these candidates are real and at high- $z$ , then the implied Ly $\alpha$  fraction at  $z \simeq 7$  is lower than measured at  $z \simeq 6$ . Red triangles and associated errors correspond to measurements that will be possible if a large percentage of z-drops expected to be discovered with future observations (e.g. ULTRA-VISTA and WFC3 MCT) are followed up with spectroscopy. The quoted neutral fractions correspond to those implied from a mapping derived from McQuinn et al. (2007) and are only valid at  $z \simeq 7$ .

Attributing this decline in number density to a decrease in Ly $\alpha$  transmission (ignoring the contribution from the declining galaxy number density), we would expect see strong differential evolution in the Ly $\alpha$  fraction over  $6.6 \lesssim z \lesssim 7.0$ . In principle, the DEIMOS observations should have easily detected such a decline in the initial sample of 17 z-drops observed in October 2009. Unfortunately, as discussed earlier, the poor conditions prohibit detecting Ly $\alpha$  at  $z \gtrsim 6.6$  for the faint sources considered in this work. Therefore we are unable to verify this result with our current DEIMOS dataset.

However, the only detailed spectroscopic survey of z-drops currently in the literature (Richard et al. 2008) does offer tentative support for the downward trend in the Ly $\alpha$  fraction. In their paper, seven gravitationally-lensed z-drops were observed with the NIRSPEX spectrograph on Keck (McLean et al. 1998), and none showed evidence for Ly $\alpha$  emission (with rest-frame equivalent width limits as low as  $\simeq 30 \text{ \AA}$ ). Likewise, a similar absence of Ly $\alpha$  was seen in the  $z \simeq 6.8$  gravitationally lensed galaxy in Abell 2218 (Kneib et al. 2004; Egami et al. 2005). The typical luminosities of these sources are considerably lower than the restricted range used in Figure 15, hence one would expect them to have Ly $\alpha$  fractions that are significantly greater than those observed at lower redshifts in this figure. In contrast, we measure an upper limit to the  $z \simeq 7$  Ly $\alpha$  fraction which is suggestive of a significant decline over  $6 < z < 7$ .

At the very large equivalent width thresholds adopted in this figure, it is unlikely that this decline could be produced by incompleteness owing to the presence of OH emission lines. While these NICMOS dropouts are generally not as robust as the z-drops being identified with WFC3 (see Bouwens et al. 2009a), the lack of Ly $\alpha$  is tantalising in light of the narrowband LAE results (Ota et al. 2008). Such a marked decline in the number density of Ly $\alpha$  emitters should easily be detected in future follow-up of current WFC3 z-drop samples.

We now explore the potential ramifications that these results may have for reionisation and discuss the possibility of improving and extending the  $x_{Ly\alpha}$  measurements in the future. We first discuss how one may use these measurements to quantify changes in the IGM. Various theoretical studies have examined how an increase in the neutral fraction of the IGM impacts the transmission of Ly $\alpha$  photons (e.g., Santos 2004; Furlanetto et al. 2006; McQuinn et al. 2007; Mesinger & Furlanetto 2008). In this paper, we consider the models of McQuinn et al. (2007), which make use of 200 Mpc radiative transfer simulations to compute the effect of inhomogeneous reionisation on the transmission of Ly $\alpha$  photons and the clustering of Ly $\alpha$  emitting galaxies. In Figure 4 of their paper, McQuinn et al. (2007) present the Ly $\alpha$  luminosity function at  $z = 6.6$  for various HI fractions, ranging from  $x_{HI} = 0.00$  to  $x_{HI} = 0.88$ . The greater the HI fraction, the more the amplitude of the Ly $\alpha$  luminosity function decreases with respect to the fully-ionised case. The relative amplitude of the luminosity functions for various ionisation fractions is directly related to the decreased transmission of Ly $\alpha$  photons associated with reionisation of the IGM. For example, the amplitude of the Ly $\alpha$  luminosity function decreases by a factor of  $\simeq 120$  when the HI fraction increases to 0.88.

Our goal is to translate the measured Ly $\alpha$  fractions into estimates of the ionisation state of the IGM. We can convert the McQuinn et al. (2007) results into a mapping between Ly $\alpha$  fraction and  $x_{HI}$  as follows. First, we naively assume that in the absence of any change in the ionisation of the IGM, the Ly $\alpha$  fraction would not evolve between  $z \simeq 6$  and  $z \simeq 7$  (see below for an alternative approach). We then assume that the predicted decline in the amplitude of the Ly $\alpha$  luminosity function (with respect to when the IGM is fully ionised) will result in an identical decrease in the Ly $\alpha$  fraction. Hence if the HI fraction is 0.88 at  $z \simeq 7$ , we should expect the Ly $\alpha$  fraction to be  $120\times$  lower than its measured value at  $z \simeq 6$ , when the IGM is ionised. With these assumptions, the current measurements at  $z \simeq 6.5$  indicate that the IGM is still largely ionised.

However given that the Ly $\alpha$  fraction evolves with redshift in the absence of changes in the IGM ionisation state, our ‘no-evolution’ assumption above is clearly simplistic. Indeed if the dust obscuration continues to evolve over  $z \gtrsim 6 - 8$  (as implied by Bouwens et al. 2010a), then in the absence of IGM ionisation state evolution, the Ly $\alpha$  fraction is likely to be even larger at  $z \simeq 6.5 - 7$ . If this is the case, then the mapping between Ly $\alpha$  fraction and IGM ionisation state discussed above would be incorrect. To account for this, we extend the smooth evolution seen in the Ly $\alpha$  fraction over  $4 \lesssim z \lesssim 6$  (when the IGM is highly ionised) to  $z \simeq 6.5$  and  $z \simeq 7$ . We adopt this prediction as the baseline  $x_{Ly\alpha}$  value consistent with an ionised IGM. We associate

deviations below this value with evolution in the IGM ionisation state in a similar manner as above. Following this approach, the lack of Ly $\alpha$  in the Richard et al. (2008) sample and Kneib et al. (2004) source suggests  $x_{\text{HI}} > 0.3$  at  $z \simeq 7$ .

With new ground-based surveys (e.g. UltraVISTA) and WFC3 programs set to reveal hundreds of  $z$  and Y-drops in the next several years, it should be possible to derive accurate Ly $\alpha$  fractions over the redshift range  $6 \lesssim z \lesssim 8$ . Indeed, we estimate that feasible campaigns with optical and near-IR multi-object spectrographs should easily be able to detect Ly $\alpha$  equivalent widths as low as 30-50 Å (rest-frame) for a sample of 200  $z$  and Y-band dropouts with continuum magnitudes spanning  $26 \lesssim m \lesssim 28$ , enabling much improved statistics on the fraction of LBGs with Ly $\alpha$  emission and the possibility to measure Ly $\alpha$  fractions as low as  $\simeq 1\%$ . With such a spectroscopic sample, it will be easy to identify whether the Ly $\alpha$  fraction at  $6.5 \lesssim z \lesssim 8$  shows a deficit with respect to measurements at  $z \simeq 5 - 6$ . In fact, this dataset would enable the characterisation of Ly $\alpha$  fractions more than  $10\times$  lower than those expected at  $z \simeq 7$  in the absence of any change in the IGM ionisation state (Figure 15). With these results, it should be trivial to identify the differential evolution in the Ly $\alpha$  fraction that would be expected from reionisation; in the context of the simulations of McQuinn et al. (2007), these results enable the IGM ionisation state to be tracked between fully ionised ( $x_{\text{HI}} \simeq 0.0$ ) and almost completely neutral ( $x_{\text{HI}} \simeq 0.8$ ).

## 6 SUMMARY AND CONCLUSIONS

In this paper, we have presented a new technique aimed at constraining reionisation. By measuring the luminosity-dependent fraction of continuum dropouts with strong Ly $\alpha$  emission at  $z \simeq 4, 5, 6, 7$ , and so on, we are sensitive to sudden changes in the transmission of Ly $\alpha$  photons that would be expected if the ionisation state of the IGM changes, complementary to past efforts to link evolution in the Ly $\alpha$  luminosity function to reionisation (e.g. Malhotra & Rhoads 2004; Kashikawa et al. 2006; Iye et al. 2006; Ota et al. 2008). The spectra not only provide information on Ly $\alpha$  but also reveal constraints on the absorbing gas along the line of sight and provide a robust spectroscopic sample for derivation of stellar populations (e.g. stellar masses, ages). Through this information, we seek to simultaneously provide insight into the evolution of the most important factors governing Ly $\alpha$  transmission (dust obscuration, HI covering fraction and kinematics), and to thereby better isolate the impact of the IGM ionisation state on the evolving Ly $\alpha$  fraction.

To complete this Ly $\alpha$  fraction test, we have conducted a large Keck/DEIMOS spectroscopic survey of dropouts in the GOODS-S and GOODS-N fields. The current Keck/DEIMOS sample includes 268 B-drops, 95 V-drops, 64  $i'$ -drops, and 17  $z$ -drops and uniquely extends to faint continuum magnitudes ( $M_{\text{UV}} \simeq -18$ ). When combined with existing VLT/FORS2 spectroscopic observations of B, V, and  $i'$ -drops in the two GOODS fields, our sample contains 627 dropouts. We summarize our key findings below.

1. We present tentative spectroscopic identification of a  $z$ -drop identified in the GOODS ERS imaging CDF-S (Wilkins et al. 2010a). The galaxy shows a  $7\sigma$  emission fea-

ture at  $z = 6.44$ , consistent with the photometric redshift expected from the broadband imaging. If confirmed, this would be the first WFC3  $z$ -drop with spectroscopic identification in the literature. Future deep spectroscopic study of WFC3 dropouts should vastly increase the number of Ly $\alpha$  emitters in this redshift regime.

2. The prevalence of Ly $\alpha$  emitters is greater among low luminosity galaxies. We find that the fraction of dropouts with Ly $\alpha$  equivalent widths in excess of 50 Å increases from  $\simeq 10\%$  at  $M_{\text{UV}} \simeq -21.5$  to  $\gtrsim 40\%$  for sources fainter than  $M_{\text{UV}} \simeq -19.5$ . This result is consistent with previous studies comparing the UV and Ly $\alpha$  luminosity function for samples of narrowband Ly $\alpha$  emitters (Ouchi et al. 2008). This finding demonstrates that a large fraction of galaxies at the faint-end of dropout samples are likely very similar to the high-EW and UV-faint LAEs found via narrowband filters.

3. We find that the fraction of strong Ly $\alpha$  emitters at fixed luminosity moderately increases toward earlier time in the redshift range  $3 \lesssim z \lesssim 6$ . Binning our sample in two redshift ranges ( $3.0 < z < 4.5$ ) and ( $4.5 < z < 6.0$ ), we find that the fraction of Ly $\alpha$  emitters with rest-frame equivalent width in excess of 50 Å increases in each luminosity bin considered.

4. We examined the possibility that these luminosity and redshift-dependent trends are driven by evolution in the dust obscuration of high-redshift galaxies. We find that the  $z \simeq 4$  sources with strong Ly $\alpha$  emission have considerably bluer UV slopes, implying significantly less dust extinction. This result is consistent with a range of observational studies (e.g., Shapley et al. 2003; Pentericci et al. 2009; Kornei et al. 2009). In light of recent results revealing that dust obscuration decreases toward lower luminosities and higher redshifts (Reddy & Steidel 2009; Bouwens et al. 2009b), it appears that dust evolution plays a major role in governing the Ly $\alpha$  fraction.

5. We discuss the possibility that the covering fraction of hydrogen may be lower in low luminosity galaxies. In more luminous galaxies, strong Ly $\alpha$  emission is generally coupled with low dust extinction and low equivalent width ISM absorption lines (Shapley et al. 2003), the latter of which appears to arise from a non-uniform covering fraction of neutral hydrogen (Quider et al. 2009). Given the increased prevalence of strong Ly $\alpha$  emitters and low dust obscuration at low luminosity, this result may suggest that galaxies with a non-uniform covering fraction may be much more common among UV-faint systems. Strong Ly $\alpha$  emitters with UV faint continua do appear to show weak low-ionisation ISM absorption (Stark et al. 2010, in preparation), but higher S/N and higher resolution spectra of gravitationally lensed galaxies are required to directly measure the covering fraction. We note that if the covering fraction of hydrogen is indeed lower for low luminosity galaxies, this would in turn imply that Lyman continuum photons may more easily escape from feeble galaxies, a trend that appears to be seen in  $z \simeq 3$  galaxies with deep Keck spectra (Steidel et al. 2010, in preparation).

6. We have measured the fraction of  $z$ -drops with strong Ly $\alpha$  emission in our spectroscopic sample, enabling us to constrain  $x_{\text{Ly}\alpha}$  at  $z \simeq 6.5$ . The estimated Ly $\alpha$  fraction appears consistent with the redshift trend seen over  $3 \lesssim z \lesssim 6$ . However the current sample is far too small to rule out a decline to  $z \simeq 6.5$ . Efforts to extend these studies to  $z \simeq 7$  have

thus far failed to locate Ly $\alpha$  emission. The lack of strong Ly $\alpha$  in the Keck spectra of 7 candidate LBGs in Richard et al. (2008) and the lensed  $z \simeq 6.8$  source in Kneib et al. (2004) provides tantalising evidence that the Ly $\alpha$  fraction declines by  $z \simeq 7$ . The availability of more robust WFC3/IR  $z \simeq 7$  samples (e.g. Oesch et al. 2010; McLure et al. 2010; Bunker et al. 2010) enables this possibility to be readily tested with the new generation of near-infrared multi-object spectrographs.

7. Using recent simulations linking the evolution in the abundance of Ly $\alpha$  emitters to the IGM ionisation state (McQuinn et al. 2007), we examine the possibility of placing constraints on reionisation with our spectroscopic sample. While we emphasize that the results are strongly model-dependent, if the evolution in the Ly $\alpha$  fraction at  $z \simeq 7$  were to hold up, the McQuinn et al. (2007) simulations would suggest that the neutral fraction of the IGM is  $x_{HI} \gtrsim 0.3$  at  $z \simeq 7$ . More robust estimates of the  $z \simeq 6.5 - 7$  Ly $\alpha$  fractions are needed to confirm these preliminary findings.

The recent emergence of new photometric samples of dropouts at  $z \gtrsim 7$  with the WFC3 onboard HST provides a great deal of promise for extending this test in the future. Long exposures with upcoming near-infrared multi-object spectrographs will enable significant detections of strong Ly $\alpha$  emission lines from sources as faint as  $J \simeq 28$ , allowing the Ly $\alpha$  fraction test to be extended to  $z \simeq 8$ .

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